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Lake Restoration: A Five-Year Evaluation of the Mirror and Shadow Lakes Project Waupaca, Wisconsin

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16. ABSTRACT

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R804687-01

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ABSTRACT

Mirror and Shadow Lakes, small seepage lakes in central Wisconsin, had experienced cultural eutrophication as a result of storm water drainage. Storm sewers were diverted from the lakes in 1976 and in 1978 aluminum sulfate was applied to enhance the recovery rate by reducing internal phosphorus loading from the sediments. Mirror Lake was artificially circulated to prevent low winter oxygen concentrations and increase spring oxygen concentrations. Storm sewer diversion reduced external phosphorus loading from 58-65 percent for both lakes while the aluminum sulfate application reduced inlake phosphorus concentrations from 90 mg/m^3 and 55 mg/m^3 in Mirror and Shadow Lakes respectively to 20-25 mg/m^3. Diversion of the storm sewers resulted in a decrease in epilimnetic phosphorus and nitrogen concentrations.

Increased algal productivity and biovolume as a result of urban drainage after storm events were eliminated following storm sewer diversion. With the greatly reduced sediment phosphorus release following the alum treatment there was a decrease in spring algal community size and a shift from a community dominated by Oscillatoria agardhii var. to a more diverse community. Annual primary production was reduced 38 percent in Mirror Lake with the depth profiles shifting to those representative of mesotrophic lakes. Phosphorus and nitrogen sedimentation rates were reduced 55 percent and 28 percent respectively resulting in a decrease in the amount of these nutrients being recycled. The zooplankton community numerical size was reduced as the algal production declined.

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INTRODUCTION

In the last century, cultural eutrophication of some lakes has become a problem. With an increasing population, greater impact has been placed on our waters. With increasing nutrient loads due to perturbation of the watershed, the lakes have become less desirable owing to large standing crops of algae and macrophytes. With the increase in population and leisure time activities, has come greater awareness of lake water quality conditions and a desire to promote improvements.

The strategies and schemes for corrective action include those which control the problem sources or measures which treat only the symptoms. Perhaps one of the most frequently-applied solutions is diverting the major source of incoming nutrients away from a lake. The results can be very spectacular as in the case of Lake Washington (Edmondson, 1977) or disappointing as with Lake Norrviken (Ahlgren, 1977). In cases where nutrient diversion is not successful, the problem can be traced to continued nutrient input from the sediments.

Mirror and Shadow Lakes experienced accelerated eutrophication in recent years owing to urban storm water drainage. By the late 1960's, residents surrounding Mirror Lake complained of winter fish kills and offensive algal odors. A study funded by the Upper Great Lakes Regional Commission identified the major nutrient source as storm water runoff. The study concluded that an implementation program to restore Mirror and Shadow Lakes should include storm sewer diversion, in-lake nutrient inactivation, and artificial circulation.

Upon a request from the City of Waupaca Public Inland Lakes Protection and Rehabilitation District[1], the Wisconsin Department of Natural Resources submitted a proposed plan for the restoration of the lakes to the United States Environmental Protection Agency for partial funding under PL 92-500(314). A lake restoration grant of $215,000 from the U.S. EPA was awarded to the Lake District through the Department of Natural Resources for this project. The Department awarded an additional $130,000 to the Protection and Rehabilitation District. The Lake District locally raised an additional $85,000 to fund the restoration project.

The restoration plan included elimination of the major external nutrient source by diversion of the storm sewers, reduction of internal phosphorus loading by adding aluminum sulfate after the storm sewers were diverted, and artificial circulation in Mirror Lake to prevent winter fish kills. Storm sewer diversion was completed by December 1976 and the aluminum sulfate was applied in May, 1978.

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[1] Wisconsin law authorizes creation of Inland Lake Protection and Rehabilitation Districts as special purpose units of government to identify and remedy lake problems in 1974.

In order to adequately determine the effectiveness of the lake restoration program projects, some projects were selected for intensive evaluation and the Mirror/Shadow Lakes Project was one. A three year grant was awarded to the Wisconsin Department of Natural Resources initially but the grant was later extended for an additional two years. The objectives of this evaluation were as follows:

(1) Determine both lakes response to storm sewer diversion,

(2) Determine the effectiveness of aluminum sulfate in preventing phosphorus migration from the sediments,

(3) Determine if the nutrient control measures would effectively reduce the pelagial algal productivity and standing crop,

(4) Determine the response of the pelagial zooplankton and benthic invertebrate communities to the restorative measures.

This report will describe the effect of the rehabilitation techniques upon the ecology of Mirror and Shadow Lakes including changes in the water chemistry and the impact upon the algal and zooplankton populations. Also addressed is the lake response that might have occurred if only one of the restoration techniques had been implemented in contrast to a more holistic approach using a combination of individual lake restoration techniques.

CONCLUSIONS

1) Evidence from a sediment core from Mirror Lake indicated that this lake experienced accelerated productivity soon after storm sewers began discharging into the lake.

2) Storm sewer diversion reduced the external phosphorus loading by 65 percent in Mirror Lake and 58 percent in Shadow Lake. External nitrogen loading was reduced by 27 percent in Mirror Lake.

3) Epilimnetic phosphorus and nitrogen concentrations were reduced 50 percent and 34 percent respectively in Mirror Lake the first year following stormwater diversion.

4) With the elimination of stormwater input, the chloride concentrations have declined in Mirror and Shadow Lakes.

5) Internal loading from the sediments prior to the alum treatment was contributing 15 kg annually to Mirror Lake and 40 kg to Shadow Lake, equivalent to the loading from external sources prior to the stormwater diversion.

6) The application of aluminum sulfate reduced the phosphorus concentration from 0.090 mg/l to 0.020 mg/l in Mirror Lake and from 0.055 mg/l to 0.023 mg/l in Shadow Lake.

7) Phosphorus release as measured with _in situ_ chambers was reduced by over 90 percent in both lakes; while ammonium release rates were affected little following the aluminum sulfate treatment.

8) In Mirror Lake where the surface sediments had a high percentage of water, the alum layer settled to a depth of 3 cm into the sediment while the alum remained on top of the sediments in Shadow Lake because they were denser. Consequently dissolved phosphorus levels were higher in the bottom waters of Mirror Lake.

9) Artificial circulation in the fall prevented winter fish kills in Mirror Lake by increasing oxygen concentrations, while spring circulation increased the water temperature in the bottom waters.

10) Primary productivity was reduced and consequently the sedimentation rates of carbon, nitrogen, and phosphorus declined in Mirror Lake.

11) In Mirror Lake the size of the vernal phytoplankton community was reduced and the composition changed from a community largely dominated by _Oscillatoria agardhii_ Gom. var. to a more diverse community.

12) The _Oscillatoria_ population was markedly reduced in Mirror Lake following the alum treatment, but returned in the summer of 1981. The population seemed little affected by the rehabilitation schemes in Shadow Lake.

13) In Mirror Lake annual primary production was reduced from 210 GC/m^2 in 1978 to an estimated 130 GC/m^2 in 1981.

14) The numerical size of the zooplankton community declined in response to a reduction in the trophic status of Mirror Lake.

15) The benthic population of Chaoborus punctipennis say in Mirror Lake greatly increased from 5 organisms/m^2 to over 2,000 organisms/m^2 during the study.

16) In the four years following completion of the restoration work, both lakes showed no signs of returning to their "trophic status" of pre-1977 with the exception of the Oscillatoria population.

Site Description and History

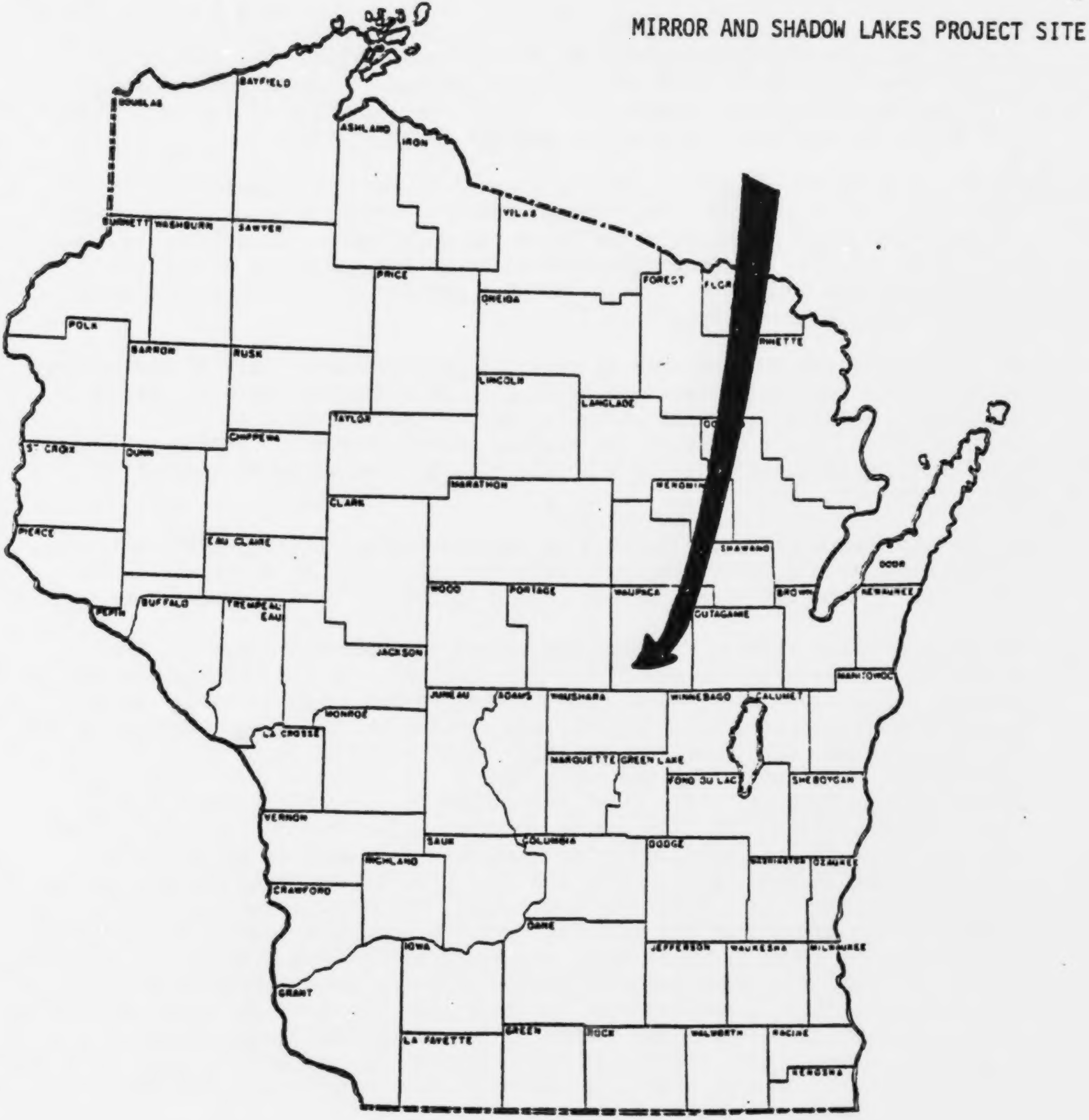
Mirror and Shadow lakes are kettle lakes that were formed during the last period of glaciation about 14,000 years ago in the pitted margin of the Cary outwash plain. This plain was formed during the recession of the Green Bay lobe of the Cary ice sheet during the Pleistocene period. The outwash plain in this area is 15-30 m thick consisting of medium to coarse grained sands interspersed with gravel lenses. This plain overlies 15 m of the Cary glacial till which in turn overlies granitic bedrock (Possin 1973).

Since the formation of Mirror Lake, a blanket of various organically-derived sediments has accumulated. Peat occurs nearly everywhere on the lake shore although the greatest accumulation is on the west shore. Underlying the near shore peat deposits and comprising the major bottom sediments are thinly interbedded sand and marls. In the deepest portion of Mirror Lake, organic muck overlies the marl (Possin 1973).

The climate of the Waupaca area is typically continental. July is the warmest month with an average temperature of 22.2°C while January, with an average temperature of -8.0°C, is the coldest. Normal precipitation is 78.7 cm (31 in) while 19 cm is the average annual snowfall. Hennings (1978) estimated evapotranspiration on a nearby seepage lake to be 90 percent of precipitation in 1972.

Mirror and Shadow Lakes are located in central Wisconsin (Figure 1), entirely within the city limits of Waupaca. Prior to settlement by white man in the early 1850's, the lakeshores were a popular place for Indian encampments.

In the 1850's and 1860's, as lumbering became an important industry, the population in the area increased rapidly. By 1885, the City of Waupaca had reached a population of 2,500 and the population was 4,400 in 1970. Streets around Mirror Lake were built by 1901 and residential building construction in the vicinity was nearly complete by 1934. Home building began later around Shadow Lake, continuing into the early 1960's. A report in 1917 described Mirror Lake as "a pure little lake" surrounded by a greenbelt (Ware 1917). From 1908 until 1913, the city pumped drinking water from Mirror Lake. From 1913 until the 1960's, drinking water was taken from shallow wells on the lakeshore, but in the 1960's, taste and odor problems occurred and use of the wells was discontinued. From 1900 until 1950, Mirror Lake was used for commercial ice production for railroad cars. By the late 1930's, the streets surrounding the lakes had been paved and storm sewers were discharging to both lakes. By 1948, the hypolimnion of Mirror Lake was anoxic below 10 m in August, and in 1955, a metalimnetic oxygen maxima was observed (Smith et al. 1975). Mirror Lake in the 1950's through the early 1970's experienced occasional winter fish kills and in 1971, both Mirror and Shadow Lakes were treated with antimycin to eradicate the rough fish population, followed by a restocking program.



MIRROR AND SHADOW LAKES PROJECT SITE

DOUGLAS
BAYFIELD
ASHLAND
IRON
VILAS
BURNETT
WASHBURN
SAWYER
PRICE
ONEIDA
FOREST
FLOR
RINETTE
POLK
BARRON
RUSK
LINCOLN
LANGLADE
OC
TAYLOR
ST CROIX
DUNN
CHIPPEWA
MENOMIN
MARATHON
CLARK
PIERCE
EAU CLAIRE
SHAWANO
DOOR
WOOD
PORTAGE
WAUPACA
BROWN
KEWAUNEE
OUTAGAMIE
PEPIN
BUFFALO
TREMPEAL EAU
JACKSON
MANITOWOC
JUNEAU
ADAMS
WAUSHARA
WINNEBAGO
CALUMET
MONROE
LA CROSSE
MARQUETTE
GREEN LAKE
FOND DU LAC
SHEBOYGAN
VERNON
SAUK
COLUMBIA
DODGE
WASHINGTON
OZAUKEE
RICHLAND
CRAWFORD
DANE
IOWA
JEFFERSON
WAUKESHA
MILWAUKEE
GRANT
LA FAYETTE
GREEN
ROCK
WALWORTH
RACINE
KENOSHA

Figure 1. Location map of Mirror and Shadow Lakes.

From the latter part of 1971 through 1973, an aeration study was conducted in Mirror Lake as part of an Inland Lake Demonstration Project (Smith et al. 1975 and Brynildson and Serns 1977). During 1972 and 1973 total and hypolimnetic aeration was utilized to prevent winter fish kills and to attempt to eliminate the anoxic conditions in the hypolimnion. An urban runoff study was conducted in Mirror and Shadow Lakes during 1972 and part of 1973 (Knauer 1975 and Peterson and Knauer, unpublished report).

PHYSICAL DESCRIPTION

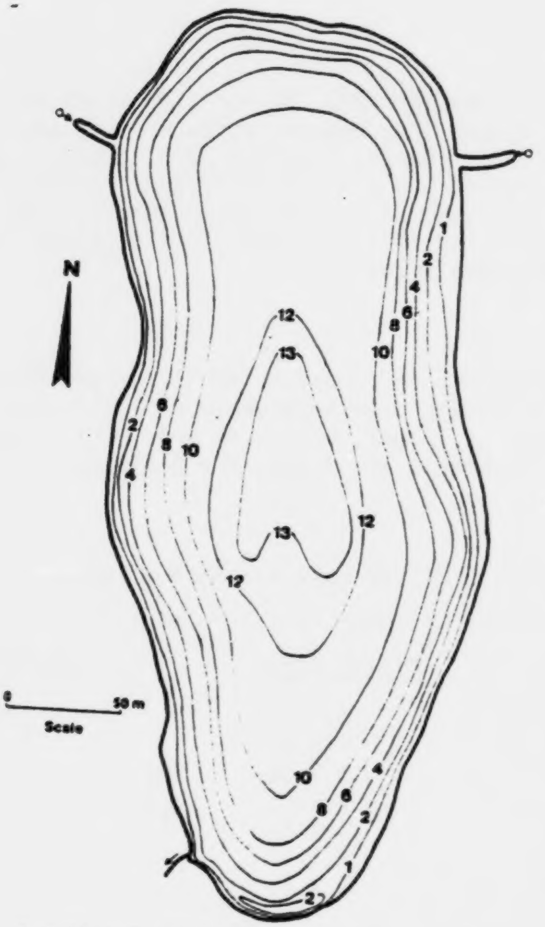
Table 1 presents the morphometric information for Mirror and Shadow Lakes. Mirror Lake is the deepest, having a maximum depth of 13.1 m and a surface area of 5.1 ha. Shadow Lake is larger, having an area of 17.1 ha and a maximum depth of 11.6 m. Figures 2 and 3 show the basin morphometry of each lake.

Table 1. Morphometric Data for Mirror Lake and Shadow Lake

	Mirror Lake	Shadow Lake
Maximum Depth	13.1 m	11.6 m
Mean Depth	7.8 m	5.3 m
Surface Area	5.1 ha	17.1 ha
Volume	$4 \times 10^5 m^3$	$9.1 \times 10^5 m^3$
Shoreline Length	1.1 km	1.9 km
Watershed - Prediversion	32.2 ha	76.9 ha
Postdiversion	13.1 ha	56.7 ha

Prior to storm sewer diversion, the drainage basin area for Mirror Lake was 32.2 ha of which 13.1 ha was not drained by the storm sewers. Other than the storm sewers, there were no streams which entered Mirror Lake. Possin (1973) concluded that in 1972 storm sewers contributed 26 percent of the hydrologic budget while diffuse surface runoff, groundwater, and direct precipitation contributed 10, 21, and 43 percent, respectively. The outlet from Mirror Lake drains into Shadow Lake although it flows only during the ice-free season and then averages only 0.01 m^3/sec.

Shadow Lake; prior to storm sewer diversion, had a drainage basin of 76.9 ha. Since the diversion, this has been reduced to 56.7 ha. Besides the stream entering from Mirror Lake, an intermittent stream also flows into the lake. The storm sewer contribution to the hydrologic budget in 1972 was computed to be 17 percent with other surface flow, direct precipitation and groundwater contributing 10, 32, and 41 percent respectively. The lake outlet flows into the Crystal River.


N
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0
50 m
Scale
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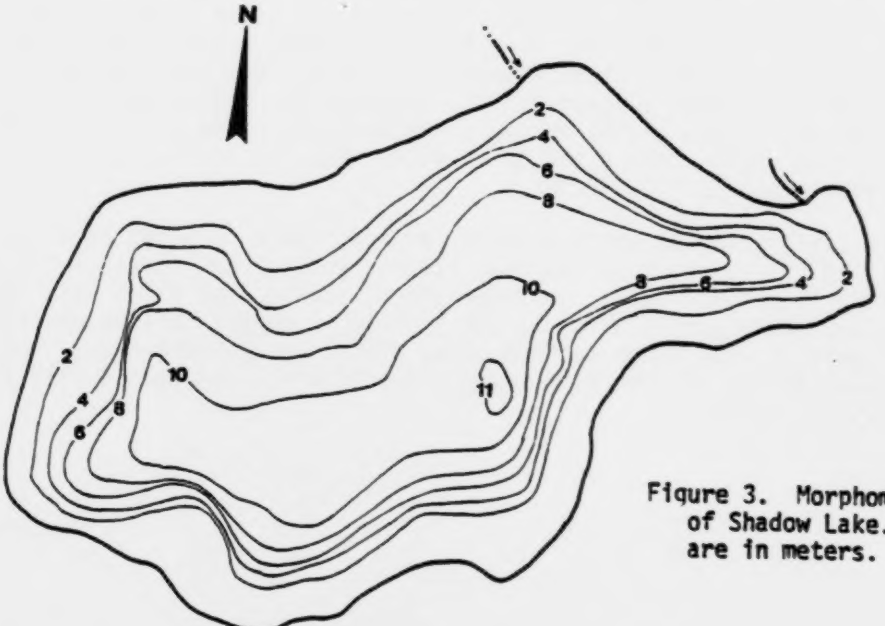
8
6
2
1
2

Figure 2. Morphometric map of Mirror Lake. Contours are in meters.


N
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100 m
Scale

Figure 3. Morphometric map of Shadow Lake. Contours are in meters.

METHODS

Water samples for physical, chemical and biological analyses were collected from the deepest portion of both lakes at monthly intervals during the periods of ice cover, except in 1980 when samples were collected only twice. During the open water period, samples were collected biweekly in 1977, 1978, and 1981, at least triweekly in 1979, and at least monthly in 1980.

Phosphorus, nitrogen, and specific conductivity analyses were conducted at the State Laboratory of Hygiene as described by Environmental Protection Agency (1974). Alkalinity was determined titrimetrically using a pH meter. The pH was determined with a Corning pH meter. On a less regular interval, iron, manganese, suspended solids, and volatile suspended solids concentrations were also determined by the State Laboratory of Hygiene. Prior to 1981, dissolved silica was determined at a Department of Natural Resources laboratory using the molybdosilicate complex method (APHA 1971), but in 1981 the analysis was performed at the State Laboratory of Hygiene. Twice during the study, concentrations of Ca, Mg, Na, K, Cl, and SO_4 were determined also at the State Laboratory of Hygiene.

Dissolved oxygen concentrations were measured by the Winkler method using the azide modification. Temperature was measured with a Yellow Springs oxygen meter equipped with an electronic thermistor.

Chlorophyll a was determined using the 90 percent acetone extraction method. Samples were filtered on site immediately upon collection and the glass fiber filter (pore size 1-3 microns) immersed in acetone and packed in ice. Following a minimum of 24 hours, the filters were pulverized with a tissue grinder and after an additional 24 hours, the absorbence was measured with a Bausch and Lomb Spectronic 70 with a slit width of 8 nm. Since this instrument underestimates the chlorophyll a absorption peak, a correction factor was applied. Chlorophyll a was computed by the phaeophytin correction method after Lorenzen (1967). Starting in November 1978, the concentration of HCl added was reduced from 1N to 0.1N following the suggestion of Riemann (1978).

Water transparency was measured using a 20 cm diameter white Secchi disc. Primary productivity was measured by the radioactive carbon method. Samples were collected at one meter intervals through the trophogenic zone (7.5 or 8.5 m during ice-free season, and 3.5 or 4.5 m during ice cover). The 300 ml samples were inoculated with approximately 6 uCi of $NaH^{14}CO_3$ and incubated from 10:00 a.m. to 2:00 p.m. CST at the depths taken. The bottles were suspended horizontally under a bar between two floats in order to minimize artificial shading. After incubation, the samples were either placed on ice (until September, 1977), or treated with 1 ml of one percent merthiolate. The amount of algal radioactive carbon taken up was first determined using the acid bubbling technique of Schindler et al. (1972). This proved unsatisfactory, so after July, 1977, a portion of the sample was filtered through a 47 mm membrane filter (0.45 u pore size). The filters were washed with a minimum of 200 ml deionized water, and immediately dissolved in a dioxane base liquid scintillation fluor described by Schindler (1966). In November 1979, it was found that washing the filters with water did not remove all the radioactive inorganic carbon. There after the samples were fumed with HCl after Wetzel (1965). Since nonfuming overestimated production by ten percent, all previous production rates were revised downward by this amount. The radioactivity was measured with a Packard liquid scintillation spectrophotometer and efficiency was determined using the channel ratio method (Herberg 1975). The initial inorganic carbon concentration was determined from total alkalinity, pH, and temperature, using the equation of Rainwater and Thatcher (1959). Daily photosynthesis was computed by the method of Schindler and Nighswander (1970) using the ratio of solar radiation during the incubation period to total day radiation using a pyranometer located on the lake shore.

Phytoplankton biovolume was determined by approximating the geometric forms of individual plankters from samples preserved with acidic Lugol's solution and applying the estimated volume to cell counts. Species composition was estimated using the Utermöhl technique (Lund et al. 1958) with an inverted phase contrast microscope (Wild M40). A minimum of 100 cells of the most dominant organism were counted. Phytoplankton organisms were identified to the lowest practical taxonomic division. Taxonomic keys used included Hustedt (1930), Huber-Pestalozzi (1941), Skuja (1948), Smith (1950), Prescott (1962), Patrick and Reimer (1966 and 1975), and Weber (1971).

The zooplankton population was sampled with a Wisconsin net (76 micron pore size) with an opening diameter of 15 or 12.7 cm towed vertically from at least the depth that the lake became anaerobic. Two tows were combined before identification and enumeration. One percent of the total sample was counted using a Sedgwick-Rafter cell and compound microscope. Copepods were divided into naupliar, copepodide, and adult stages. Taxonomic keys used included Brooks (1957), Deevy and Deevy (1971)-Cladocera;, Brandlova et al. (1972), Torke (1976), and Smith and Fernando (1978)-Copepoda; Edmondson (1959) and Chengalath, et al. (1971)-Rotifera.

Eight sediment cores were taken for determining aluminum distribution in Mirror Lake along a transect in 1977 and 1979. Five cores were also taken for determining aluminum distribution from Shadow Lake along a transect across the lake. The analyses of these cores, which were divided into 5 cm sections, in Mirror Lake were performed by the Soil and Plant Analysis Laboratory of the University of Wisconsin, Madison. The 1977 core from Shadow Lake was divided into 2 cm sections and the 1979 core was divided into 5 cm sections.

Sediment release of phosphorus and nitrogen was measured in situ using the nutrient release chambers similar to those used in Shagawa Lake (Sonzogni et al. 1977). These chambers are cylindrical with a surface area of one square meter and a height of 91.4 cm. The chambers are open on the bottom and about one-half of the chamber is submerged in sediment. The water volume inside the chamber was about 500 liters. The chambers are sampled by SCUBA divers using a 500 ml stainless steel syringe. Two chambers were placed in each lake. The chambers were at a depth of 13 m in Mirror Lake and between 9 and 10 m in Shadow Lake.

Sedimentation traps were similar to those used in "Project Hypo" (Braidech et al. 1972). These consisted of cylindrical-shaped containers, 12.5 cm long with an internal diameter of 7.4 cm. Inside the trap were enough small glass tubes to fill a trap. These tubes were used to reduce turbulence within the trap, thereby minimizing resuspension of settled material.

Several traps (4-9) were postioned together in the deep holes of the lakes just above the bottom. During the latter part of the summer of 1981, a set of traps were suspended just below the trophogenic zone (8.5 m) in Mirror Lake. Because of the development of a large pelagial algal population at this depth, these traps could not be used. The traps were exposed in the lake for periods ranging from two days to over one year. The rack in which the traps were situated was positively buoyant and was attached by a line which ran through a ring on a submerged block which in turn fastened to a permanent buoy. Retrieval simply required detaching the line at the surface buoy and allowing the traps to float to the surface. Initially, one trap in each rack was inverted (bottom open, top covered) to check for periphyton growth. Because of the lack of growth, this was discontinued.

Upon returning to the laboratory, the traps were mixed together and the composite sample was analyzed in duplicate for phosphorus, nitrogen, suspended solids, volatile suspended solids, and organic carbon.

A macrophyte survey was conducted in August of 1977 and 1978 in both lakes using a modification of the line intercept method (Lind and Cottam 1969; Nichols and Mori 1971). In Mirror Lake, transects were 100 m apart and the line sampled at one meter intervals. In Shadow Lake, transects were 100 m apart and the line sampled at two meter intervals.

Benthic organisms were sampled annually in March in the deep area of each lake with a 231 cm^2 Ekman dredge. Eight different samples were taken from the lake during each sampling period.

Concentrations of phosphorus and ammonium-nitrogen in the sediment interstitial water were measured in situ using equilibration chambers similar to those described by Winfrey and Zeikus (1977). The approach consisted of an established vertical series of 21 chambers placed in the sediments for about one week. The chambers were 0.9 cm wide and 1.6 cm apart, allowing samples to be taken every 2.5 cm. The chambers were filled with deionized water and sealed with a dialysis membrane. Prior to placement in the sediments, the chambers were bubbled with nitrogen to remove dissolved oxygen. Sampling of one chamber before being put in the sediments was carried out to insure a lack of phosphorus or nitrogen in the water. Phosphorus and ammonium ions pass through the membrane from the interstitial water into the chambers via osmosis until an equilibrium is reached. Immediately upon retrieval, the water was extracted from the chambers with a syringe, and the samples placed on ice.

PALEOLIMNOLOGY

Mirror Lake, like many lakes near population centers, has undergone cultural eutrophication during the last century. A description of Mirror Lake in 1917 characterized it as a clear lake (Ware 1917). However, by 1960, occasional winter fish kills were occurring.

Using ^{210}Pb and ^{137}Cs, the sedimentation rate in the last 100 years was estimated (Garrison 1980). Prior to 1945 (8 cm below present sediment surface) the sedimentation rate was 0.064 cm/yr. Since then, the rate has increased to 0.30 cm/yr. These sedimentation rates, while probably correct in indicating an increase in recent years, may not be indicative of the whole lake basin because of sediment focusing (Lehman 1975). Focusing occurs because sedimenting particles tend to accumulate more rapidly in the deepest part of a lake; the degree to which this occurs is dependent on the lake basin morphometry.

This increase in sedimentation roughly coincides with the introduction of the storm sewers into Mirror Lake. The combination of increased inputs of solids and growth-stimulating nutrients are responsible for the observed increase in the sedimentation rate. Figure 4 shows the organic matter, specific pigment degradation products (SPDU), and oscillaxanthin profiles in a core from Mirror Lake. The analytical methods for these parameters are described in Garrison (1980). Organic matter and SPDU (a representation of algal chlorophyll) increased sharply after the introduction of urban storm drains to the lake.

At the time the SPDU and organic matter were increasing (around 1945), oscillaxanthin became more abundant in the sediments (Figure 4). Oscillaxanthin is a photosynthetic pigment found only in the blue green algal group, Oscillatoriaceae. In Mirror Lake Oscillatoria sp. was found to be an important part of the phytoplankton in 1972, the first year records are available (Knauer 1975). Sediment cores from Lake Washington have shown an increase in oscillaxanthin at about the time Oscillatoria rubescens and O. agardhii standing crops became predominant in the water column (Griffiths et al. 1969). It would seem that Oscillatoria sp. became a significant part of the phytoplankton shortly after the storm sewers were introduced into Mirror Lake. While maximum values of oscillaxanthin found in Lake Washington sediment were 40 ug/g, the Mirror Lake sediment had over 200 ug/g of oscillaxanthin. Maximum inlake concentrations of Oscillatoria were estimated to be more than two fold reported for Lake Washington (Griffiths et al. 1969).

Farris (1981) has described the diatom stratigraphy for Mirror Lake in the upper 88 cm (Figure 5). He divided the core into three distinct paleolimnological periods. The first period (88-66 cm below the present sediment-water surface) was characterized by planktonic diatoms typical of nutrient-poor lakes. A second zone (66-18 cm) was dominated by epipelic diatoms indicating the lake may have been shallower or at least had a much larger littoral area. The first part of the third period (18-8 cm) was dominated by diatom species usually found in well-mixed lakes. The species assemblage may present indicate the lake was not historically meromictic as it was generally thought in 1972. The second part of the third period, which begins at 8 cm, is dominated by Fragilaria crotonensis and Asterionella formosa which are characteristic of north temperate lakes which have experienced gross anthropogenic disturbance (Pennington 1943). This zone also exhibits a decrease in species diversity and an increase in the araphidineae/centrales ratio of Stockner (1971), as well as previously mentioned increases in organic matter, SPDU, oscillaxanthin, and the sedimentation rate.

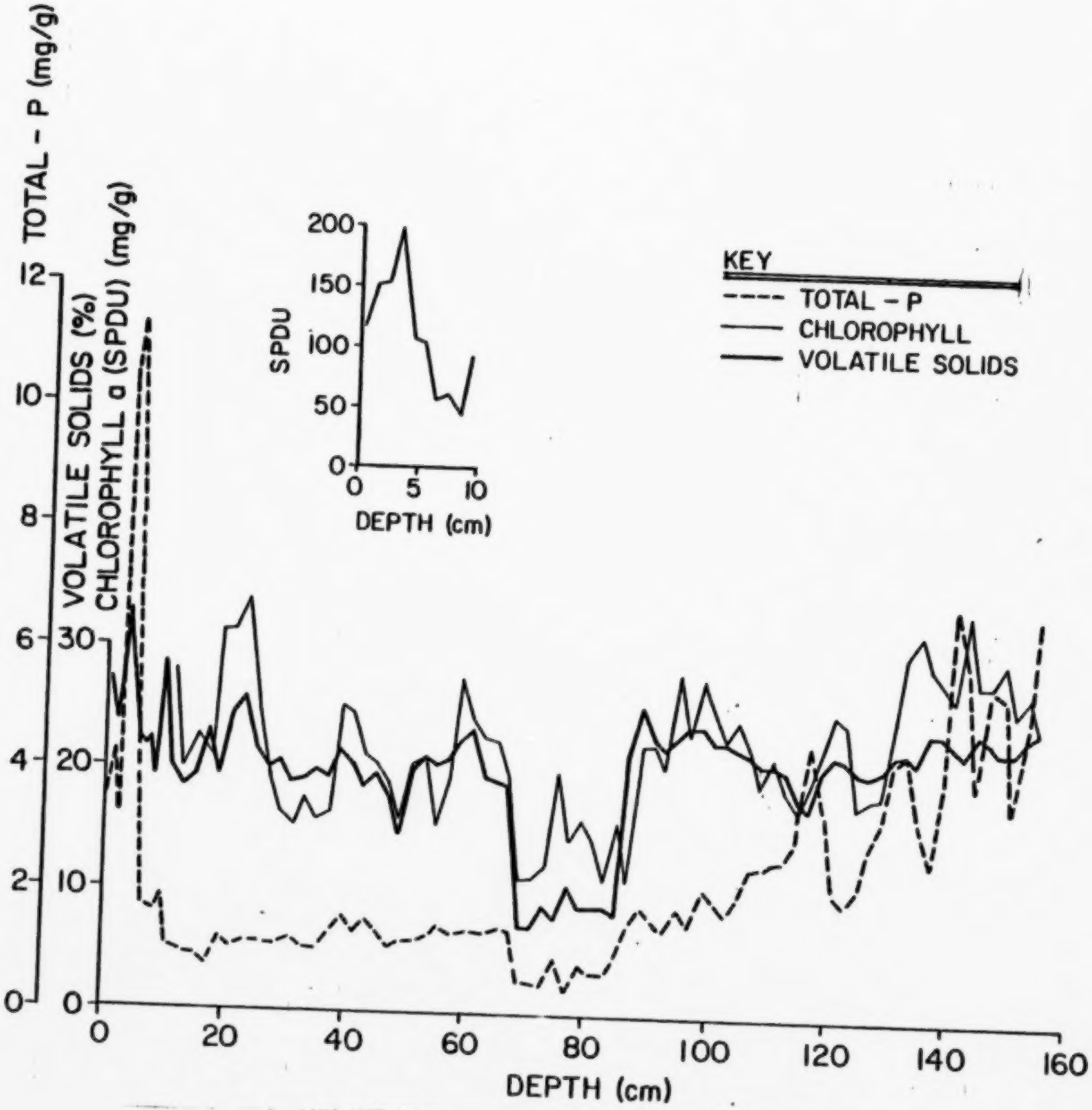


Figure 4. Total phosphorus, chlorophyll degradation products, and volatile solids in a sediment core from Mirror Lake.

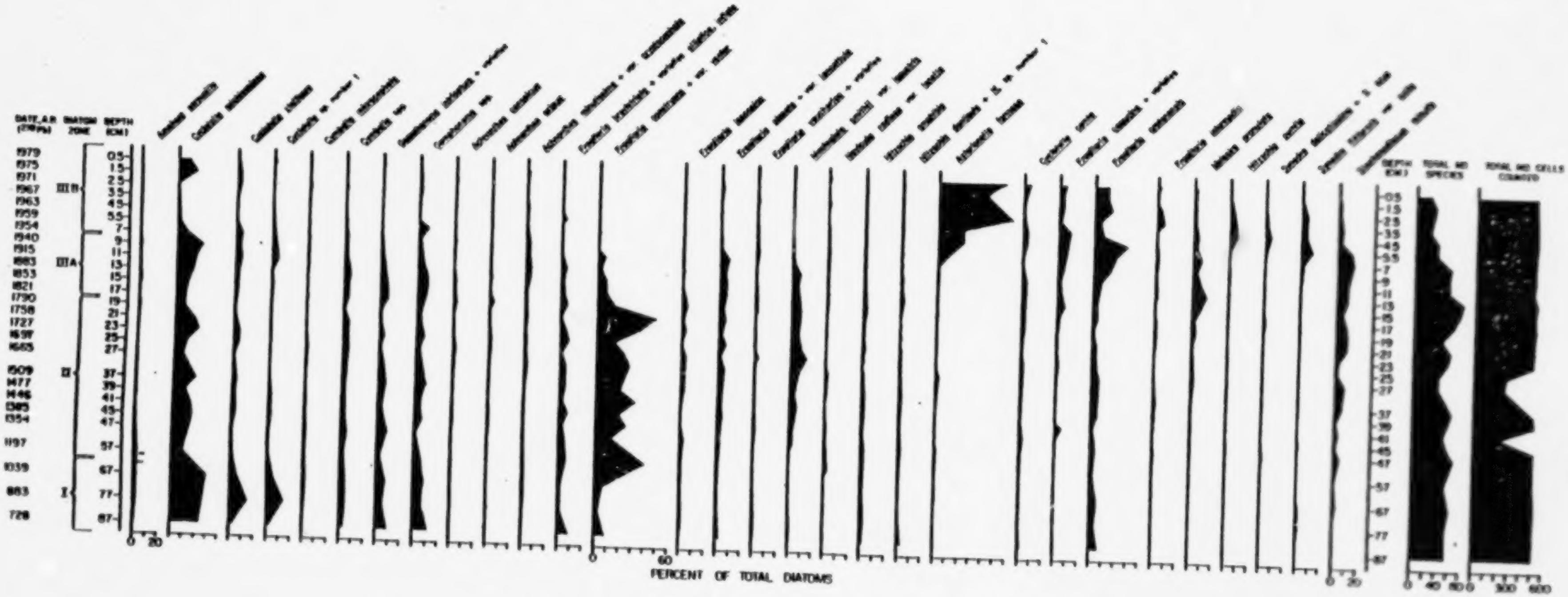


Figure 5. Diatom stratigraphy of Mirror Lake.

LAKE REHABILITATION TECHNIQUES

The lake improvement practices implemented in Mirror and Shadow Lakes were storm sewer diversion, aluminum sulfate (alum) treatment, and in Mirror Lake only, artificial circulation during vernal and autumnal mixing periods. These specific practices were recommended on data gathered in previous studies (Smith, et al. 1975; Brynildson and Serns, 1977; and Peterson and Knauer, unpublished report).

Two storm sewer basins emptied into Mirror Lake and one basin discharged into Shadow Lake (Figure 6). The storm sewer runoff from these basins was diverted away from the lakes to the Waupaca River by laying two separate, reinforced concrete sewer lines under the streets as indicated by the shading in Figure 7. The storm sewer diversion was completed in December 1976 (Table 2).

Table 2. A Breakdown of Rehabilitation Costs

	Lake District Share	DNR Share	US EPA Share	TOTAL
Storm Sewer Diversion	$78,405.48	$117,608.22	$196,013.69	$392,027.39
Artificial Destratification	$390.58	$585.88	$976.46	$1,952.92
Alum Treatment	$1,775.30	$2,662.95	$4,438.24	$8,876.49
Sediment Analyses	$1,082.40	$1,623.60	$2,706.00	$5,412.00
TOTAL	$81,653.76	$122,480.65	$204,134.39	$408,268.80

In order to enhance spring and fall circulation in Mirror Lake, a compressed air circulation system was installed. The unit consists of a compressor on the lake shore and 2-inch plastic pipe from the compressor to the deep area of the lake. The pipe was laid along the lake bottom and weighted with cement blocks. The end of the pipe has three 3/8-inch holes spaced about 9 inches apart. The purpose of the aeration unit is to mix the water column allowing dissolved oxygen to be distributed throughout the lake as a result of the surface reaeration and mixing action. The compressor is usually run for two to three weeks during the spring and during the fall. The aeration cost included $793.77 for electricity charges through 1979.

The aluminum sulfate (alum) treatment was performed in Mirror Lake on 17 May, and Shadow Lake 18 May, 1978. The alum was applied with two floating barges. The alum was trucked in liquid form from the chemical processing plant and transferred into four 250-gallon drums mounted on barges. The alum was gravity fed from the tanks and mixed 1:1 with lake water. This mixing was accomplished by pumping lake water directly into the lines from the alum tanks as they entered the application manifold. The alum was injected at a depth of 3 meters, the bottom of the epilimnion. Alum has proven to be ineffective in sealing sediments in the mixing zones (Knauer and Garrison 1980), therefore in order to minimize costs, only the water volume below the epilimnion was treated.

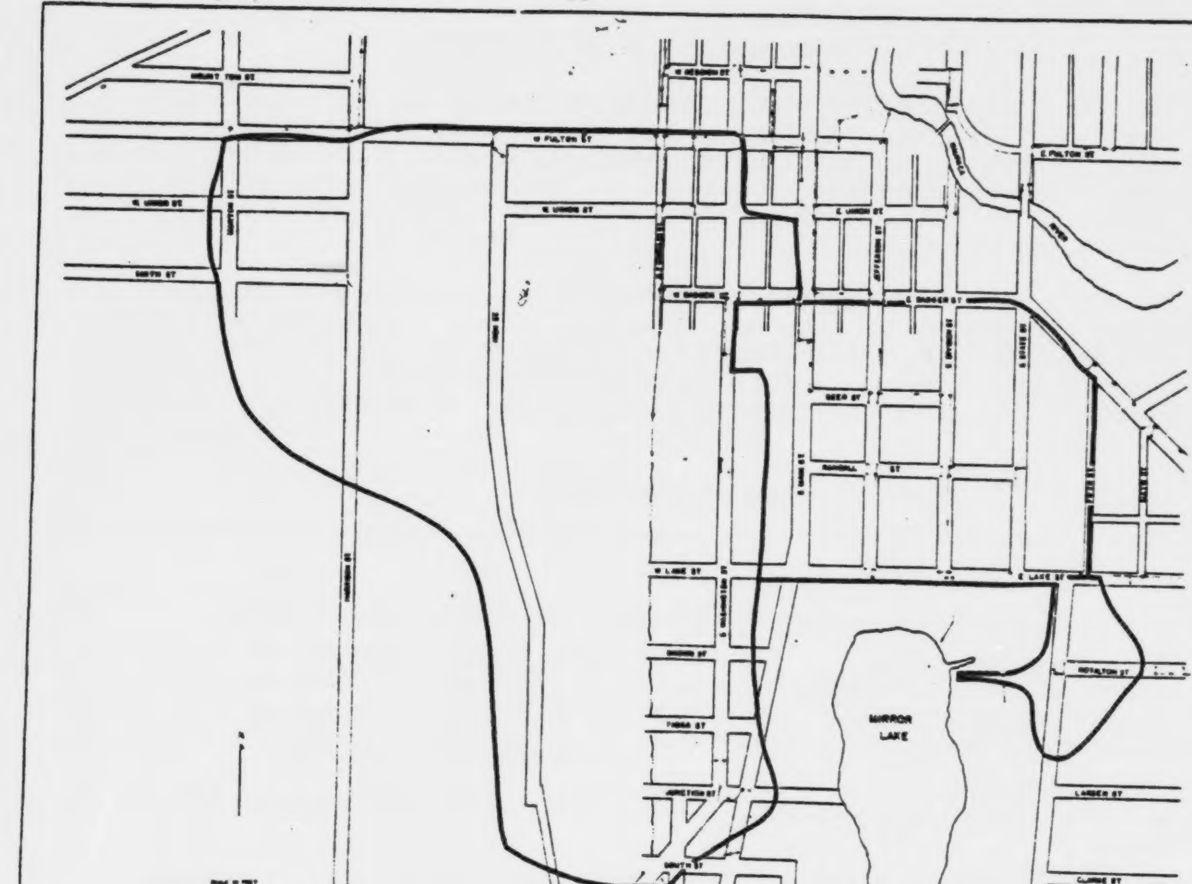
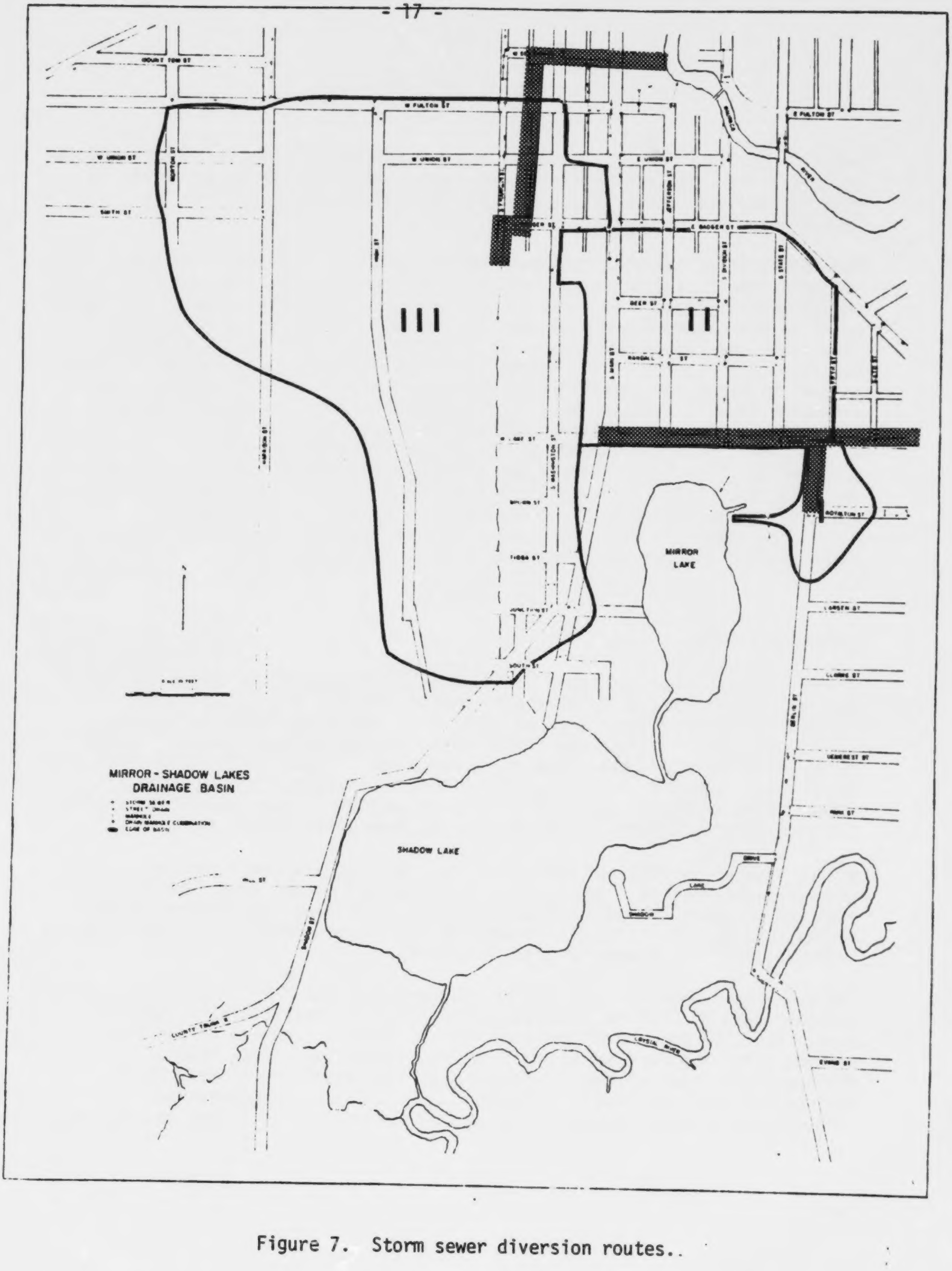

MIRROR - SHADOW LAKES
DRAINAGE BASIN
W FULTON ST
E FULTON ST
W UNION ST
E UNION ST
W LAKE ST
E LAKE ST
JUNCTION ST
CLARKE ST
MIRROR LAKE
SHADOW LAKE
COUNTY TRUNK

Figure 6. Storm sewer basins for Mirror and Shadow Lakes.


W FULTON ST
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E BADGER ST
DEER ST
RANDALL ST
III
II
MIRROR LAKE
ROYALTON ST
SHADOW LAKE
SHADOW ST
MIRROR - SHADOW LAKES DRAINAGE BASIN
STORM SEWER
STREET DRAIN
MANHOLE
EDGE OF BASIN

Figure 7. Storm sewer diversion routes..

Prior to the application, the three-meter depth contour was delineated and the lakes were divided into sections with buoys. Based on the water volume in each section, the number of barge loads was calculated to achieve the appropriate alum concentration.

The objective of the alum treatment was to restrict phosphorus transport from the hypolimnetic sediments and minimize the dissolved aluminum toxicity upon the lacustrine fauna. In order to determine the appropriate amount of alum to apply in the water column with the least effect on the pH and alkalinity, a "jar test" was performed on water from both lakes. This method which was described by Peterson et al. (1973), involves adding varying amounts of alum to lake water in the laboratory to obtain maximal phosphorus removal with a pin-point floc formation. As a result of these tests (Garrison, 1980), 40,900 kg of alum was applied to Mirror Lake and 81,800 kg applied to Shadow Lake. This corresponds to an average aluminum concentration of 6.6 mg/l and 5.7 mg/l in Mirror and Shadow Lakes, respectively. The cost of the alum, $6,206.86, was relatively inexpensive because the transportation charges were low owing to the closeness of the lakes to the chemical processing plant (74 km). The application was done by the Wisconsin Department of Natural Resources and involved about 12 man-days.

RESULTS

STORM SEWER DIVERSION

Several studies have described the high nutrient content of stormwater runoff and its relationship to to nutrient loading (McGriff 1972; Shapiro and Pfannkuch 1973; Kluesener and Lee 1974; Vital and Sprey 1974; and Oberts 1977). Shapiro and Pfannkuch (1973) found that phosphorus loadings to the Minneapolis Chain of Lakes from storm sewer runoff were 3-17 times higher than the levels suggested by Vollenweider (1968) as causing eutrophication of lakes. Kluesener and Lee (1974) concluded that 85 percent of the phosphorus influent to hypereutrophic Lake Wingra was from urban storm runoff.

During studies in 1972 and 1973 on Mirror Lake, it was found that the major source of external nutrient loading to Mirror and Shadow Lakes was from urban stormwater runoff (Knauer 1975 and Peterson and Knauer, unpublished report). During 1972 and the first five months of 1973, storm sewer runoff was measured from the three storm sewer basins (Figure 5).

The two storm sewer drainage basins that emptied into Mirror Lake comprised a combined area of 19.1 ha, consisting primarily of established residential area. About 46 percent of the land area of these basins was street and parking lots, the rest being rooftops and residential lawns. The storm drainage basin that discharged into Shadow Lake consisted of 20.2 ha of residential land and 36.4 ha of undeveloped lowlands surrounding an intermittent stream. About 7.6 percent of this basin was street and parking lots.

Table 3 lists storm sewer inputs of selected chemical parameters during 1972. A larger amount of nutrients entered via the Shadow Lake storm sewer primarily because of the larger area of the drainage basin. Runoff coefficients were lower for Shadow Lake than Mirror Lake probably because part of the drainage basin for Shadow Lake was undeveloped land. As an example, the total phosphorus runoff coefficients were 0.4 kg/ha/yr and 0.3 kg/ha/yr to Mirror and Shadow Lakes, respectively.

TABLE 3: Total Storm Sewer Input for 1972 as Kg/yr[a].

	Mirror Lake	Shadow Lake
Total Phosphorus	9.8	14.4
Reactive Phosphorus (est.)	3.3	4.8
Total Nitrogen	57	146
Inorganic N	28	62
Organic N	29	84
BOD_5	269	340
Cl	1,602	14,243
Na	775	6,714
K	85	268
Ca	290	3,447
Mg	149	1,724
Total Solids	7,648	28,576

[a] J. O Peterson, unpublished data

The storm sewer diversion was completed by December, 1976, thus reducing the watershed area (32.2 ha to 13.1 ha - Mirror Lake and 76.9 ha to 56.7 ha - Shadow Lake) consequently the nutrient loading rates to both lakes, especially phosphorus (Garrison 1980) were also reduced. Prior to the diversion, the storm sewers contributed 65 percent of the phosphorus loading to Mirror Lake and 58 percent to Shadow Lake. About 27 percent of the nitrogen loading to Mirror Lake originated from the storm sewers. With the storm sewer diversion, phosphorus loading rates were reduced to 0.120 g/m^2/yr and 0.099 g/m^2/yr in Mirror and Shadow Lakes respectively. Precipitation and surface runoff are the most important contributors to phosphorus loading at the present time (Garrison, 1980).

Because of the limited data for Shadow Lake prior to 1977, it is not possible to comment on the water quality changes immediately following storm sewer diversion. The annual average phosphorus concentration did not noticeably decline in 1977 from 1972-74 concentrations.

The first year after storm sewer diversion Mirror Lake did exhibit some improvement. The surface waters, which during much of the ice-free season are not in contact with the hypolimnion because of thermal stratification, showed a reduction in both phosphorus and nitrogen (Table 4). Phosphorus and nitrogen concentrations were reduced by 50 percent and 34 percent respectively.

TABLE 4. Mean Total Phosphorus and Nitrogen Concentrations in Mirror Lake Surface Waters, April Through November, in (mg/l).

Year	Total Phosphorus	Total Nitrogen	N:P
1972	0.057	1.14	20:1
1973	0.059	1.03	18:1
1974	0.053	0.93	18:1
1977	0.028	0.68	24:1

Knauer (1975) and Smith et al. (1975) noted that following periods of heavy rainfall and subsequent stormwater influx into the lake prior to diversion there was a large increase in phytoplankton biovolume and productivity. Figure 8 shows the seasonal trends of both these parameters and rainfall in 1977 following stormwater diversion. Algal biovolume was unresponsive to rainfall. The increase in October and November was a result of circulation of a metalimnetic algal layer into the surface waters and not increased algal standing crop. This phenomenon of incorporation of a deep algal layer into the epilimnion during the fall has also been noted by Fee (1978) in stratified lakes in Canada.

Primary productivity also was generally unresponsive to rainfall (Figure 8). Measurements indicated that primary productivity was just as likely to decrease as increase following a rain event. The greatest difference in algal productivity following storm sewer diversion is shown by productivity-depth profiles. Garrison (1978) noted that the depth profiles in 1977 were more representative of mesotrophic lakes while the 1972 profiles were indicative of an eutrophic lake. Peak productivity rates in 1972 were 60 $mg/m^3/hr$, but only 35 $mg/m^3/hr$ in 1977. Algal production generally occurred to greater depths in 1977.

ARTIFICIAL CIRCULATION

Smith et al. 1975 state that Mirror Lake seldom, if ever, mixed completely. This resulted in much of the bottom waters being anaerobic for several years. In order to replenish the oxygen in the bottom waters, the lake was usually artificially circulated for two to three weeks in November and two to three weeks following ice-out in the spring.

Figure 9 shows the dissolved oxygen isopleths for 1977 through 1981. In the spring of 1977 when the lake was not circulated, anaerobic conditions were continuously maintained below 9 meters. Because the compressor was started late in the fall of 1977, some concern was expressed about creating a water hazard during a period of ice formation. At a time when the lakes in the area were developing a total ice cover, the compressor was creating a two-acre area of open water. Consequently, the compressor was turned off after only 3 days. A few days prior to the initiation of artificial mixing, the mixed zone was naturally deepened from 8 to 10 m. Because of the introduction of oxygen-demanding substances from the hypolimnion, (e.g. H_2S) the oxygen content was depressed to 2.3 mg/l. When the compressor was turned on and the mixed zone was deepened, this low oxygen level was maintained. At the time the compressor was shut off, the weighted average dissolved oxygen for Mirror Lake was 2.6 mg/l.

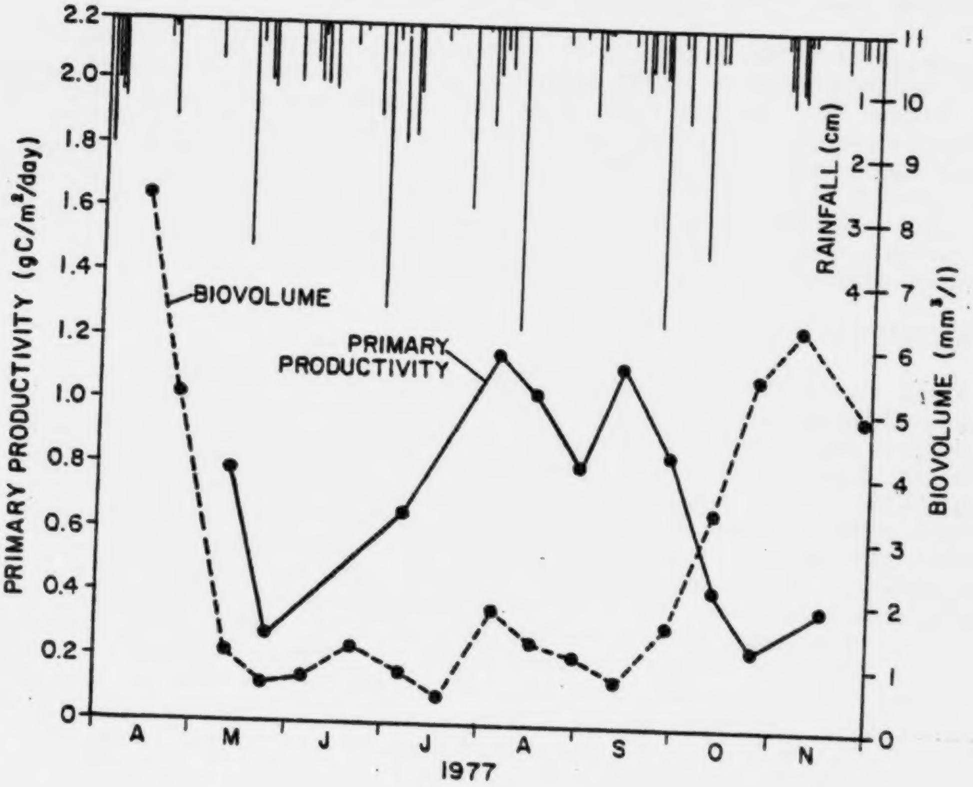

Figure 8. Precipitation, algal biovolume, and primary productivity for Mirror Lake in 1977.

Although oxygen levels were low during the ice cover, generally 1.0 mg/l, a fish kill was not observed. The spring of 1978 was the first time that the lake was destratified as intended. Dissolved oxygen concentrations of almost 10 mg/l were achieved in the bottom waters that spring, as well as the following years through 1981. Artificial circulation in the fall achieved dissolved oxygen concentrations exceeding 8 mg/l (Figure 9).

Winter fish kills had occurred occasionally in the past (e.g. 1972) because of low dissolved oxygen levels. Fall circulation has successfully prevented this occurrence in Mirror Lake even during a time when many lakes in Wisconsin exhibited fish kills, e.g. the winter of 1978-79.

A consequence of the artificially stimulated spring mixing resulted in increased temperatures in the bottom waters at the onset of stratification in May (Figure 10). Bottom water temperatures were generally about 6°C, but following circulation these temperatures have been elevated to 10-12°C, depending on the length of the mixing period. Increased bottom temperatures, coupled with the long cool fall in 1979 allowed the lake to mix naturally in November. The lake also mixed naturally in the fall of 1980. During the following winter, dissolved oxygen levels remained adequate for fish survival although this winter was also relatively mild.

ALUM TREATMENT

Smith et al. (1975) reported elevated phosphorus concentrations in the bottom waters of Mirror Lake during anaerobic conditions. Since most of this phosphorus was in soluble form, it appeared to be derived from sediment release. Other workers have noted (Mortimer 1941 and 1942; Gorham 1958; Kamp-Nielsen 1974) that as the iron and manganese are converted to their water soluble reduced forms, dissolved reactive phosphorus diffuses from the interstitial water to the overlying water. In some lakes with the reoxygenation of the deep water at turnover, iron and manganese are oxidized, making them insoluble. The oxidized iron and manganese combine with the dissolved phosphorus and co-precipitate. In Mirror and Shadow Lakes, this cycle is partially short-circuited because of hydrogen sulfide. This combines with iron during anaerobic conditions and since iron sulfide is insoluble, it precipitates. Therefore, during turnover sufficient iron and manganese are not available to precipitate all the phosphorus, leaving it available for biological uptake.

Even though over 60 percent of the external phosphorus loading for Mirror and Shadow Lakes was removed by the storm sewers, a large amount of phosphorus was contributed to the lake via sediment release (i.e. internal loading). Figures 11 and 12 show the seasonal trend of phosphorus in both lakes. During the anaerobic periods (May-September and December-March), phosphorus increased in the lakes as a result of internal loading. From June until November, 1977, the phosphorus mass in Mirror Lake increased by 15 kg, while external loading only contributed 2 kg. During the same time period, phosphorus mass increased by 40 kg in Shadow Lake, while external loading was 8 kg. During the ice-covered period in 1978, the phosphorus mass in Mirror and Shadow Lakes increased 4 kg and 26 kg respectively. While this represents considerable internal loading of phosphorus to the lakes, much of it was apparently returned to the sediment during the fall and spring. From May 1977 until May 1978, the phosphorus mass actually declined in Mirror Lake by almost 1 kg, although it increased 3.5 kg in Shadow Lake.

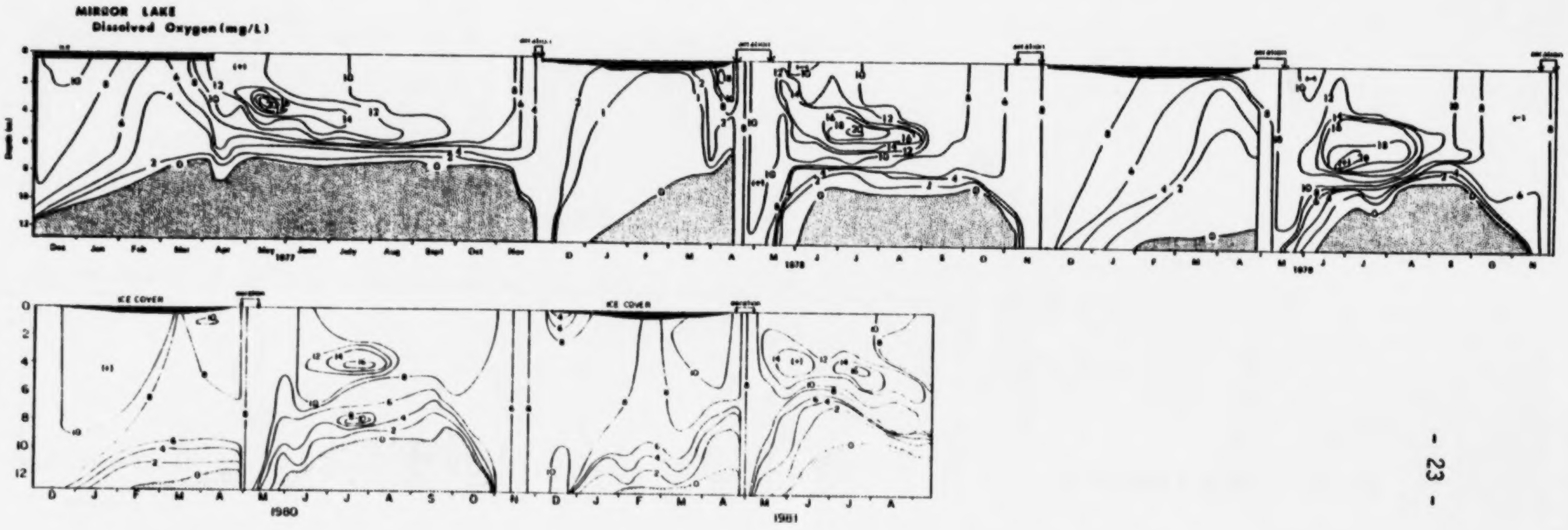

Figure 9. Dissolved oxygen isopleths for Mirror Lake.

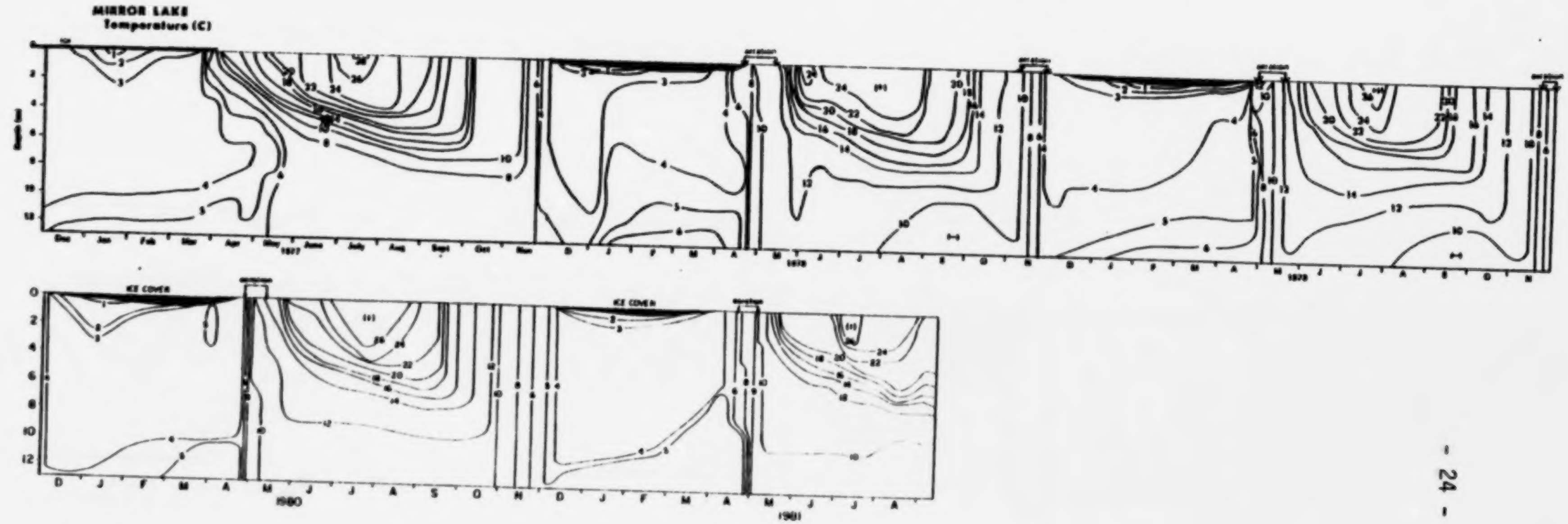

Figure 10. Isotherms for Mirror Lake.

Although much of the phosphorus released from the sediments is eventually returned, it contributes to a large algal population, especially in the spring. In order to reduce this algal bloom, aluminum sulfate was added to both lakes. It was hoped that the alum treatment would reduce the inlake phosphorus concentration and the resultant alum layer on the sediments would retard the release of phosphorus from the sediments.

The addition of the alum to the lakes did reduce the inlake phosphorus concentrations in both lakes. About 4 kg of phosphorus was removed from the water column in Mirror Lake in the first 24 hours following the treatment, and 4.5 kg of phosphorus in Shadow Lake. Figures 13a and 13b show the phosphorus trend just before the alum treatment and two weeks after the application. While phosphorus concentrations did decrease, there was not an immediate decline. In the two weeks following the treatment, phosphorus had decreased 53 percent in Mirror Lake and 30 percent in Shadow Lake. The sedimentation traps which were placed in Mirror Lake 24 hours after the alum treatment indicated some aluminum hydroxide remained in suspension. Examination of Figures 11 and 12 show that phosphorus continued to decrease until September in both lakes.

Although the phosphorus level was higher in Mirror Lake than in Shadow Lake prior to the treatment, the post-treatment concentration was the same (about 20-30 ug/l) and has been maintained. The average annual phosphorus concentration in Mirror Lake prior to the alum treatment ranged from 88 ug/l to 93 ug/l, but following treatment, the annual mean was 20 ug/l, a reduction of 78 percent. The reduction is not as dramatic in Shadow lake because the pretreatment phosphorus concentrations were lower. Pretreatment concentration was 55 ug/l and post-treatment concentration was 23 ug/l; a reduction of 58 percent.

Most of the phosphorus removed was not a result of the removal of inorganic phosphorus, but instead the physical entrapment of particulate matter by the aluminum hydroxide floc. In fact, prior to the alum treatment dissolved reactive phosphorus was undetectable in both lakes. The removal of the particulate matter is particularly evident from a sediment core. In a 10 cm core taken in Mirror Lake with a Jenkins corer, the aluminum hydroxide floc was visible in the 3 cm slice. At this level, accelerated levels of phosphorus, volatile solids, and chlorophyll degradation products were evident (Figure 14).

Sediment cores were taken along a transect in both lakes (Figure 15) were unsuccessful in determining the aluminum distribution following the alum treatment (Figures 16 and 17). In most instances, aluminum concentrations were higher in 1977 than in 1979. Often the maximum aluminum concentration was in the top core slice, both in the pretreatment core and post-treatment core. Aluminum concentrations were higher in the deeper waters, but this would be expected without the alum treatment since aluminum is usually associated with finer particles which tend to settle in the deeper waters (Delfino et al. 1969).

The failure of applied aluminum to show up in the cores is probably because the concentration of aluminum is small compared to the background concentrations. Since background levels are high and the form of aluminum normally present is nontoxic, it would not be expected that alum treatments in these and similar lakes would be detrimental to benthic invertebrates. This has been verified by Narf (1978).

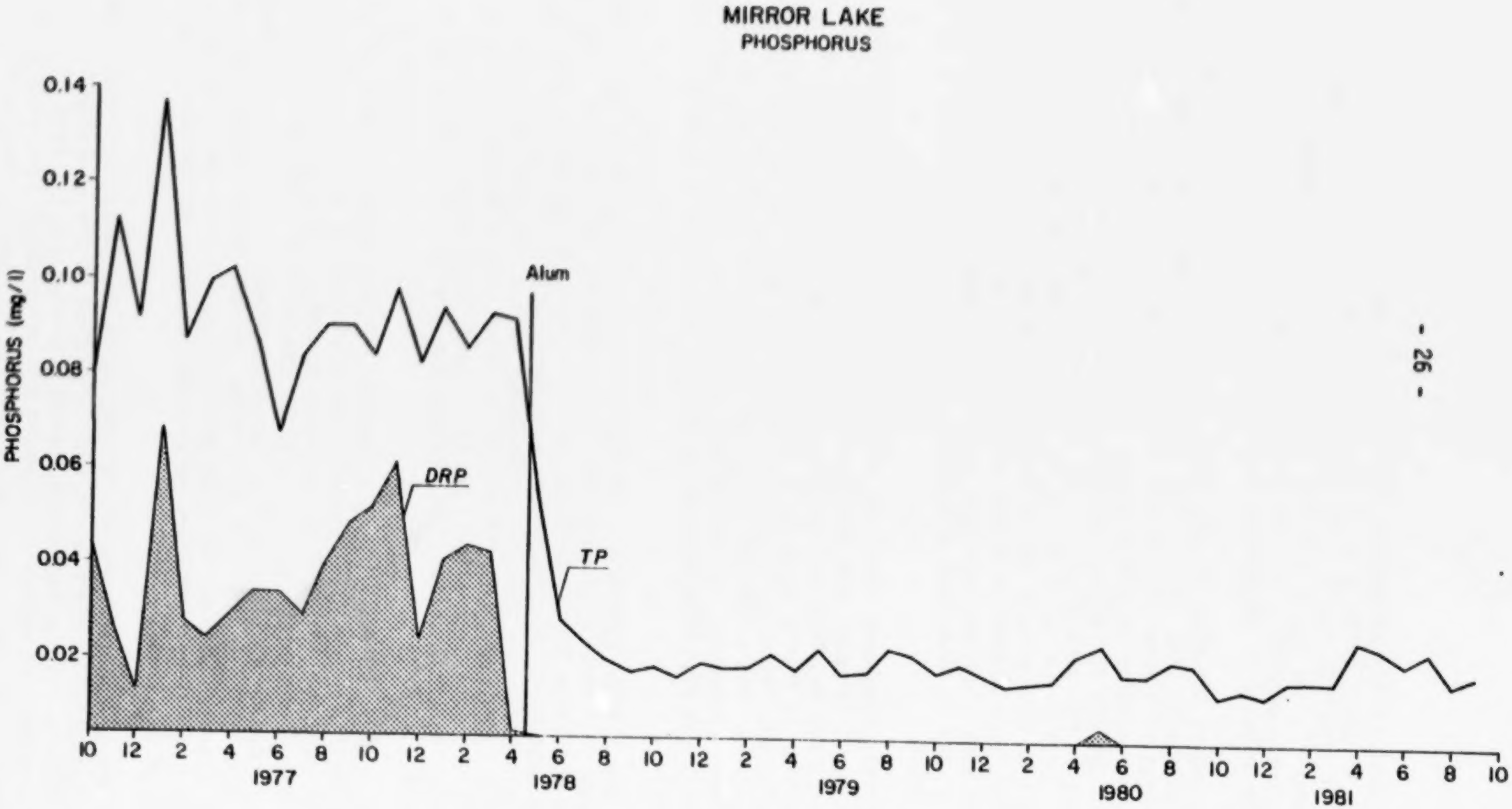

Figure 11. Weighted mean phosphorus concentration for Mirror Lake.

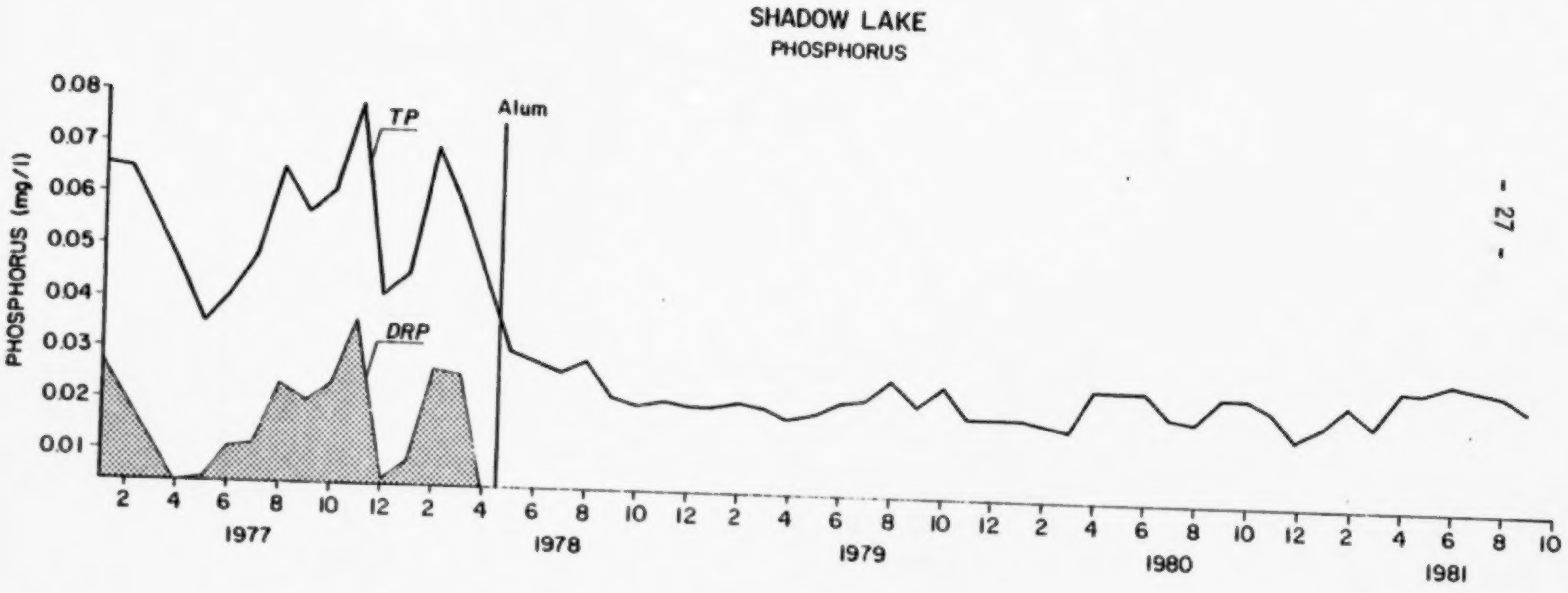

Figure 12. Weighted mean phosphorus concentration for Shadow Lake.

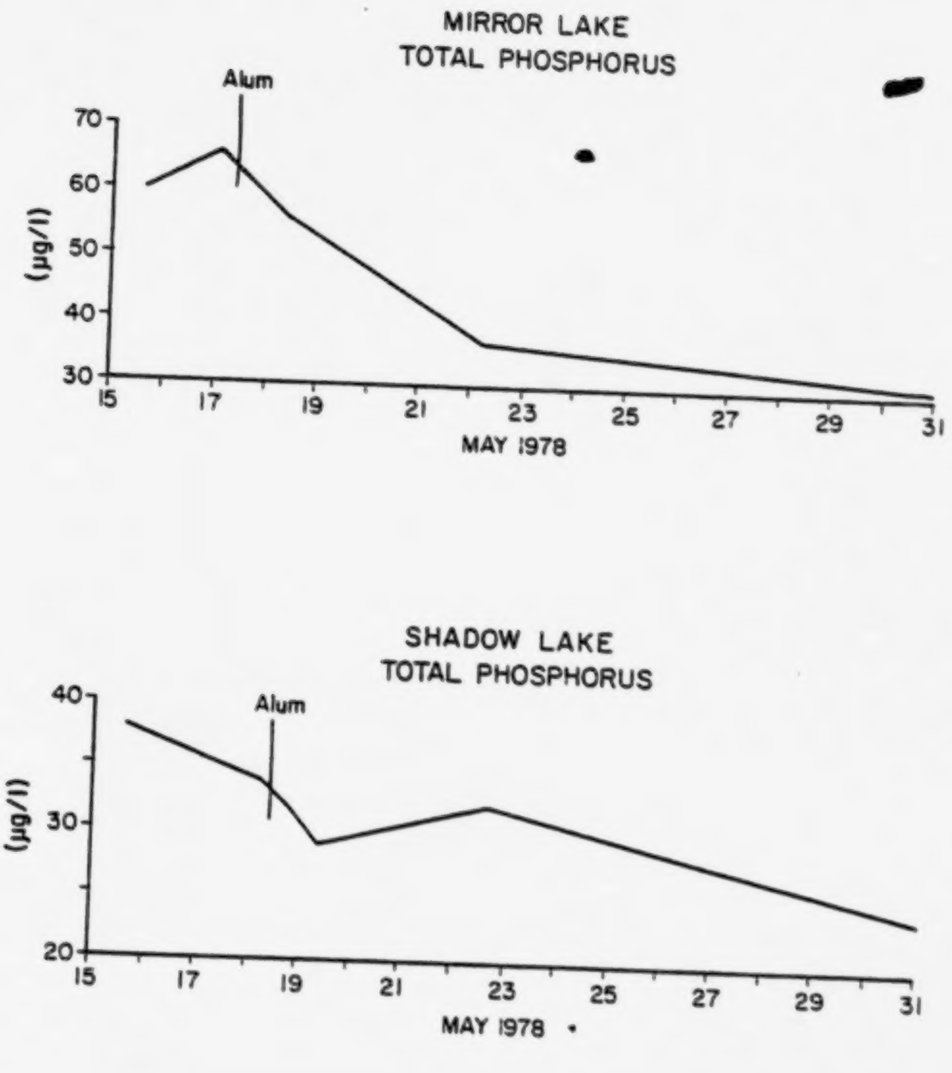

Figure 13. Total phosphorus concentrations in Mirror and Shadow Lakes before and after alum treatment.

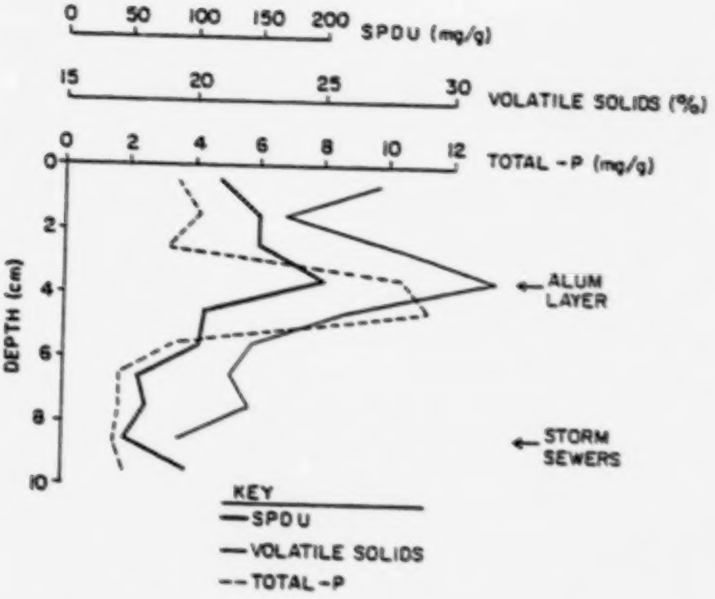

Figure 14. Total phosphorus, chlorophyll degradation products, and volatile solids in the upper sediments of Mirror Lake.

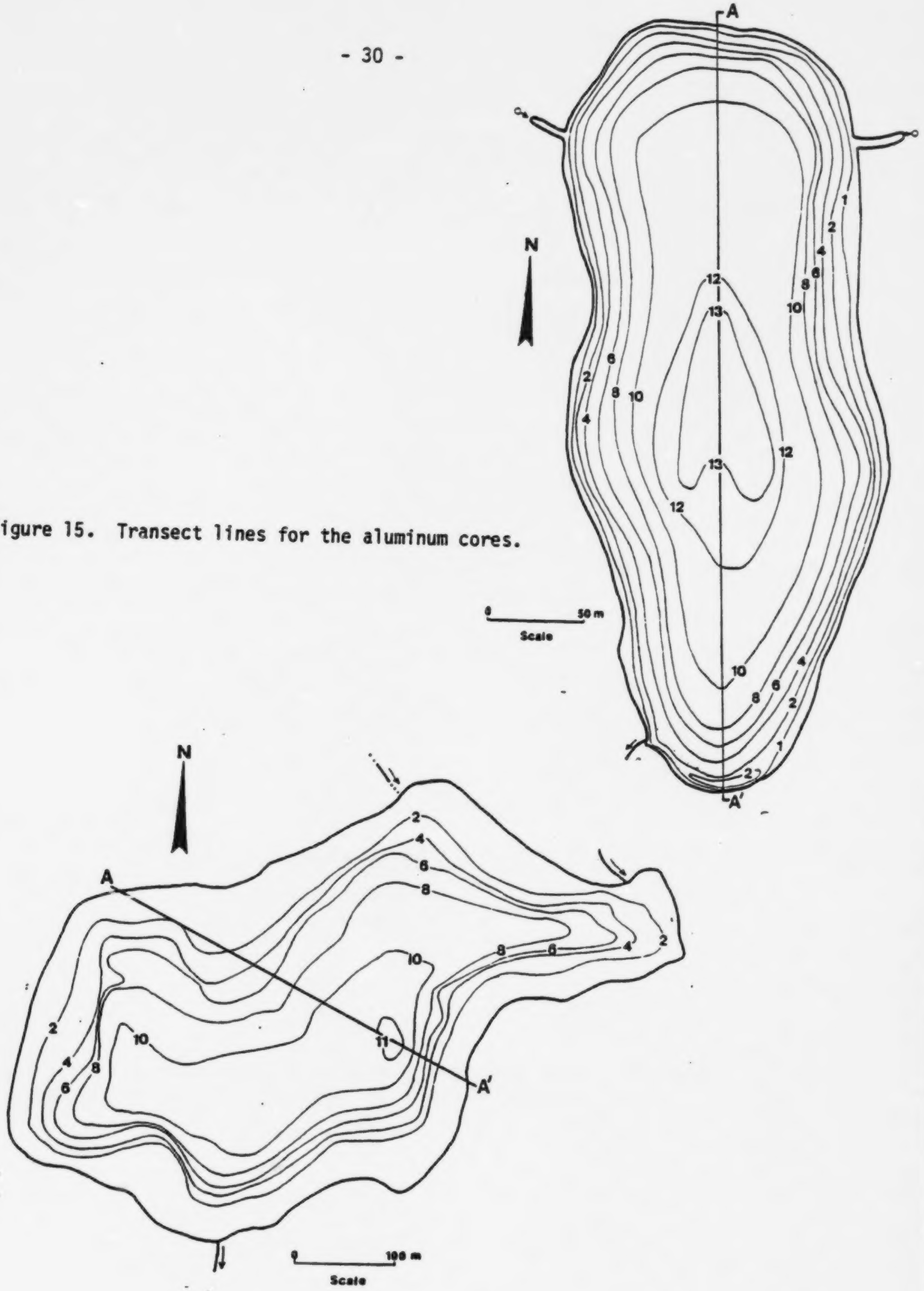
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Figure 15. Transect lines for the aluminum cores.

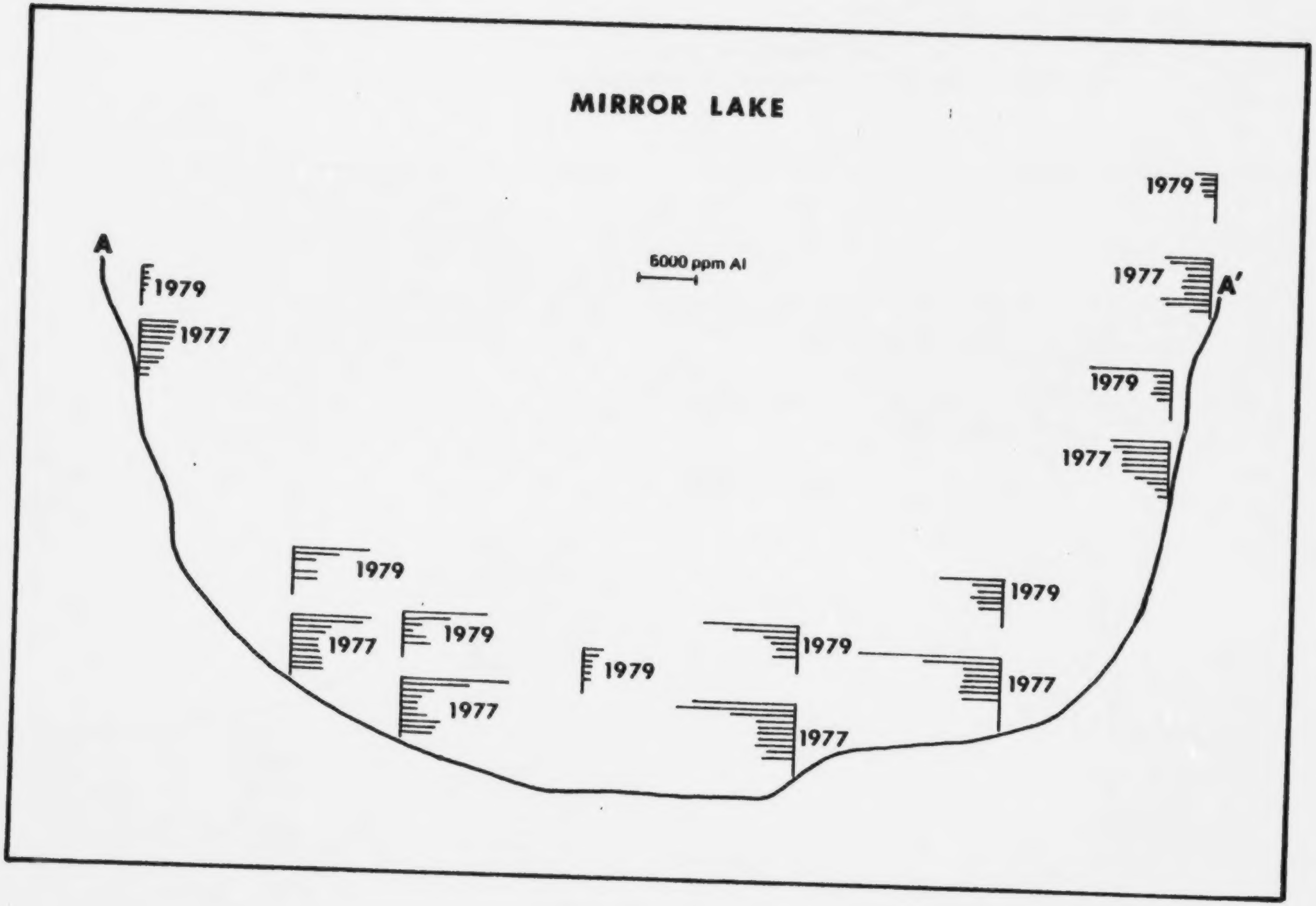


Figure 16. Aluminum concentrations in sediment cores taken before and after alum treatment in Mirror Lake.

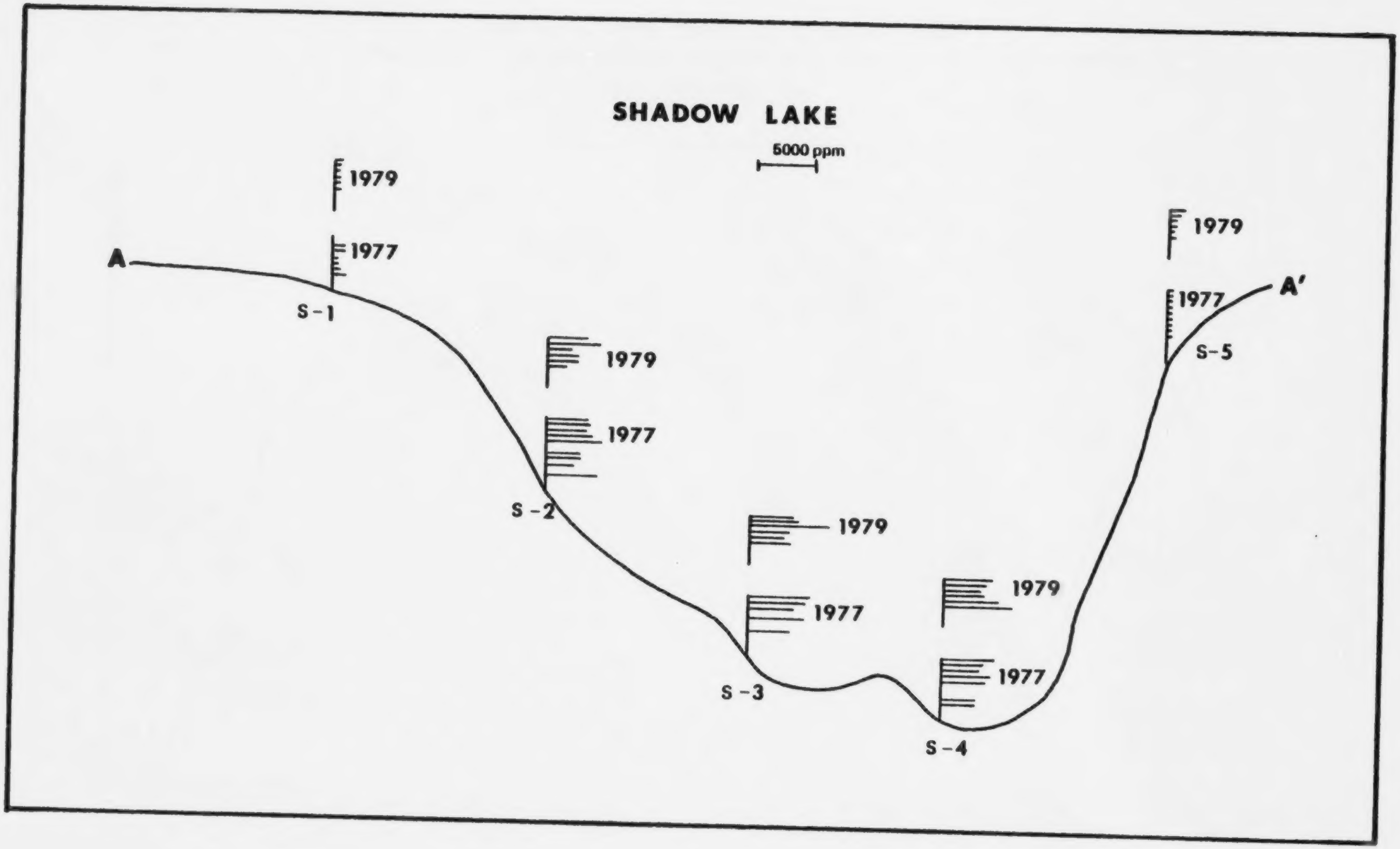


Figure 17. Aluminum concentrations in sediment cores taken before and after alum treatment in Shadow Lake.

Sediment cores taken with a Jenkins corer showed that the aluminum hydroxide floc did not necessarily remain on the surface of the sediments. In cores taken in the deepest areas of Mirror and Shadow Lakes, the aluminum hydroxide layer was visibly evident at 3 cm, but not above this. In another core taken between the 8-10 meter contour interval of Shadow Lake, the aluminum hydroxide layer was on top of the sediments. These sediments appeared to be firmer than those in the deepest portion of both lakes. Frink (1969) and Loring and Nota (1973) have observed that organic matter tends to accumulate in the deepest portion of lakes because of its fine-grained nature. This would result in the shallower sediments being more dense (Table 5). The surface sediments are indeed denser in the shallower depths of Shadow Lake. Since most of the central area of Mirror Lake is of the same depth, one would expect the alum layer to be below the surface sediments. In Shadow Lake, the zone of maximum depth is very small and most of the central area is a plateau which contains the denser sediments. Therefore, the aluminum hydroxide layer would be on top of the sediments in most of Shadow Lake. The sediments above the aluminum hydroxide layer would be able to release phosphorus into the overlying waters during anaerobic conditions. The dissolved reactive phosphorus (DRP) concentrations indicate that more phosphorus is being released from the Mirror Lake sediments than in Shadow Lake (Figures 18 and 19). In both lakes, since the alum treatment, DRP has been almost undetectable in most of the water column. The exception is the water immediately above the sediments in Mirror Lake. Since about 3 cm of sediment is above the aluminum hydroxide layer over much of the lake bottom, a small amount of DRP migrates from the interstitial water into the bottom waters from these surface sediments. This does not happen in Shadow Lake because the alum layer is on top of the sediments over much of the lake bottom. Even though some phosphorus is released from the sediments during anaerobic conditions in Mirror Lake, the maximum observed value was 0.054 mg/l. This is greatly reduced from pretreatment values which exceeded 0.480 mg/l in both lakes.

TABLE 5. Water Content of Surface Sediments in Mirror and Shadow Lakes.

Location	Percent Water
Mirror Lake, 13 m	90.8
Shadow Lake, 11.5 m	93.2
Shadow Lake, 9 m	88.1

Table 6 presents the release rates of phosphorus and ammonium-nitrogen before and after the alum treatment. In 1978 in both lakes a chamber was placed on the sediments before the alum treatment and another one on top of the sediments after the alum treatment. While there was some variability in the release rates, the release of phosphorus was much lower following the alum treatment in both lakes.

The effectiveness of the alum layer in preventing the movement of sediment phosphorus into the overlying water is illustrated by the depth distribution of phosphorus in the interstitial waters (Figure 20). In Mirror Lake, the phosphorus concentration in the interstitial water immediately above the alum

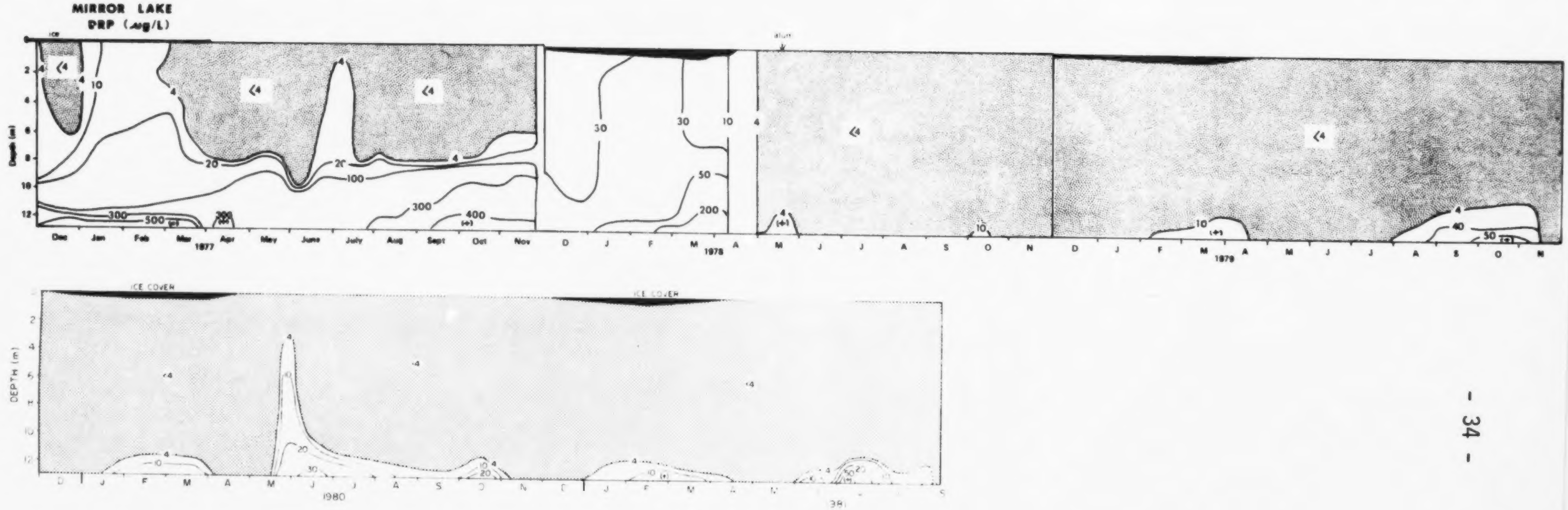


Figure 18. DRP isopleths for Mirror Lake.

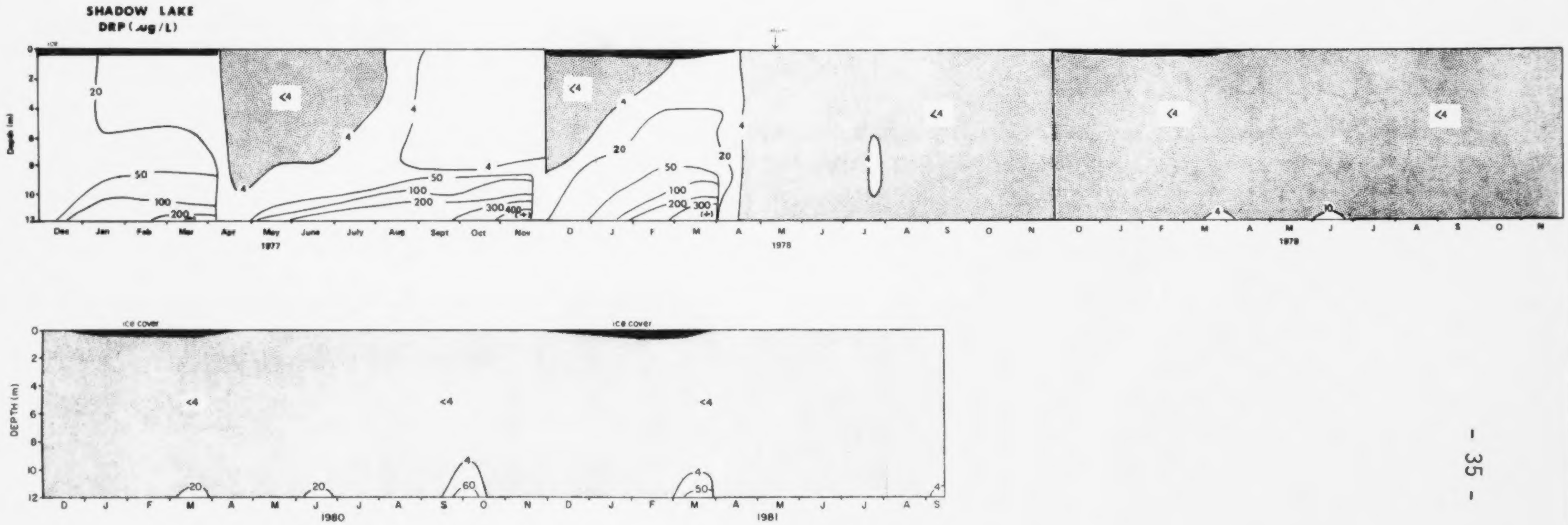


Figure 19. DRP isopleths for Shadow Lake.

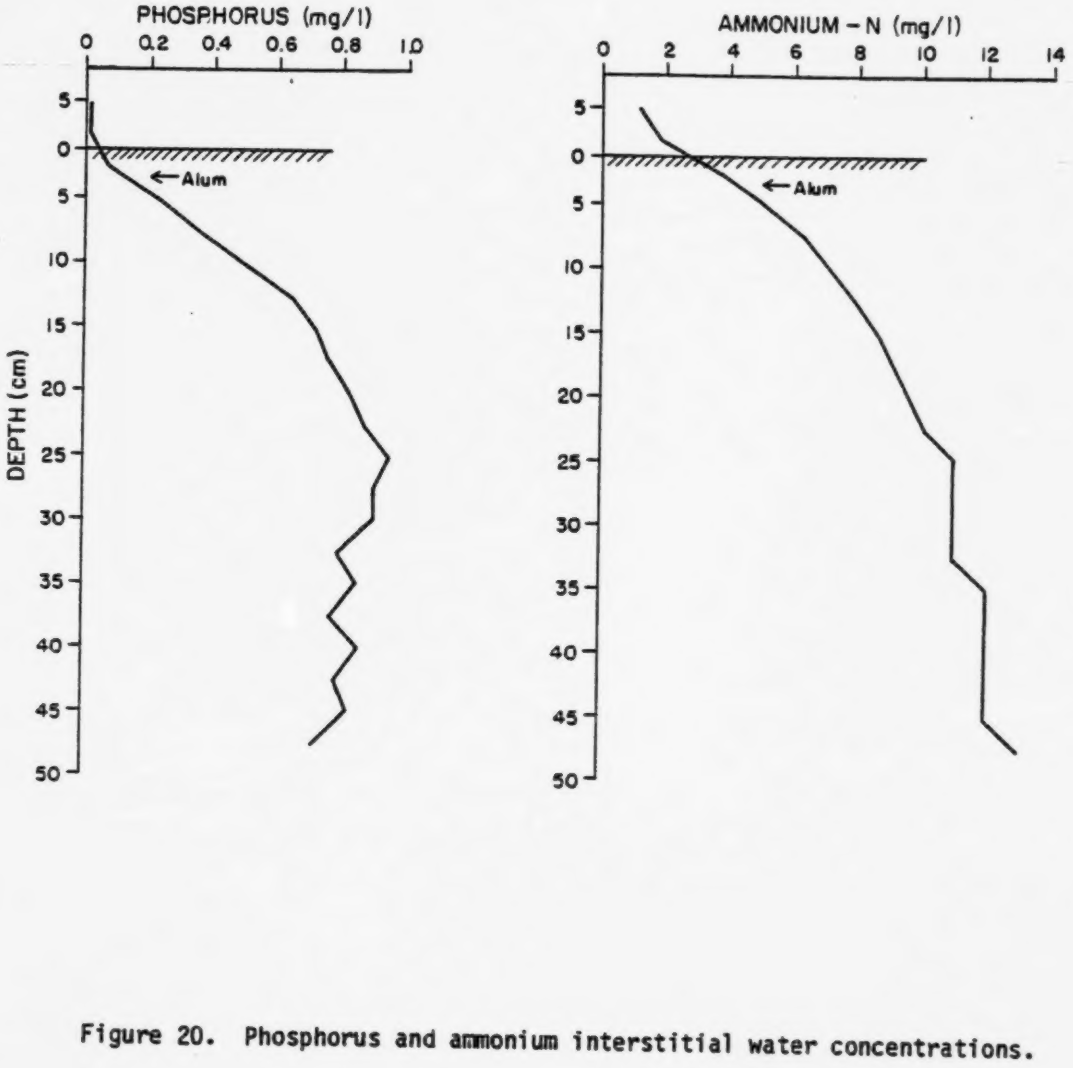


Figure 20. Phosphorus and ammonium interstitial water concentrations.

layer was similar to the concentration in the overlying water. Below the alum layer the concentrations increased significantly. While ammonium - N concentrations also showed an increase, it was less, indicating a preferential inhibition of phosphorus migration. In Shadow Lake where the alum layer is at the mud surface, the phosphorus concentration increased below the mud surface.

When aluminum sulfate is added to water, the aluminum and sulfate dissociate with the sulfate combining with the hydrogen ions and producing sulfuric acid. This results in a lowering of the pH and alkalinity. If the alkalinity becomes completely titrated, the pH will decrease and Al^{+3} will become soluble. In a soluble state, the Al^{+3} is toxic to aquatic fauna. The amount of alum added to Mirror and Shadow Lakes was carefully metered and alkalinity and pH measurements were frequently taken to assure the proper dosage was applied. Figures 21a and 21b show how the alkalinity and pH responded to the alum application in Shadow Lake. There was a rapid depression of both the pH and alkalinity values at the depth the alum was applied (3 meters) and a smaller depression down to 9 meters. The lowest pH value observed was 6.5, a decline from 8.3 and the lowest alkalinity value was 96 mg/l, a decline from 169 mg/l. The minimum pH and alkalinity values were 6.8 and 165 mg/l, respectively, in Mirror Lake.

Table 6. Nutrient Release Rates from *in situ* Nutrient Release Chambers.

Mirror Lake

Year	Total Phosphorus (mg/m^2 /day)	Ammonium-Nitrogen (mg/m^2 /day)
1977	1.30	6.6
1978 alum	0.03	4.4
1979	0.13	6.4
1980	0.04	4.5
1981	0.07	4.9

Shadow Lake

Year	Total Phosphorus (mg/m^2/day)	Ammonium-Nitrogen (mg/m^2/day)
1978 Control	1.27	8.8
alum	0.14	8.9
1979	0.18	7.4
1980	0.07	4.1
1981	0.08	7.5

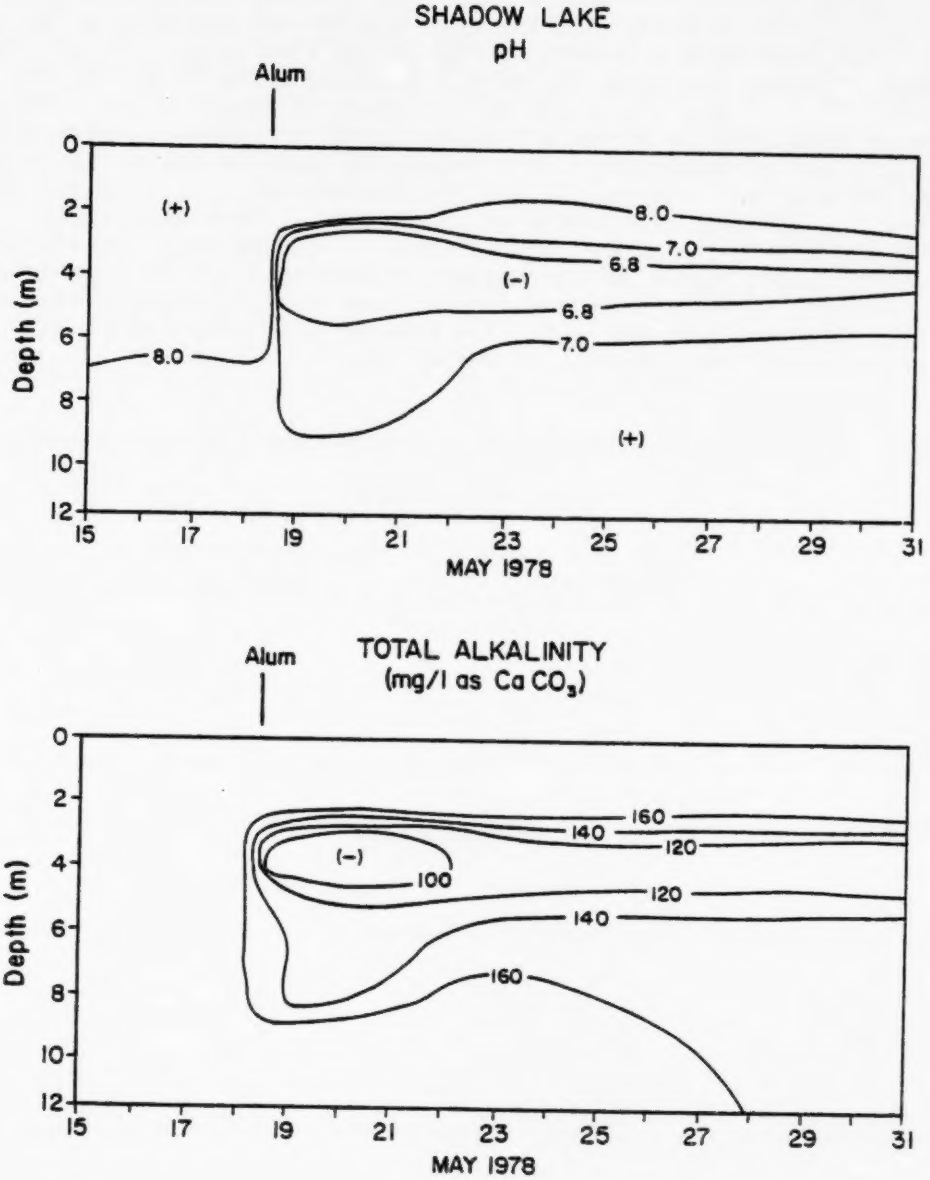


Figure 21. Alkalinity and pH in Shadow Lake before and after the alum treatment.

WATER CHEMISTRY

Both Mirror and Shadow Lakes are hardwater lakes in the range of 200-250 mg/l. The dominant cation is calcium although equal amounts of magnesium may be present in the epilimnion during the summer because of biologically induced calcium carbonate saturation and subsequent precipitation (Table 7). In Mirror Lake, sodium is found in concentrations only slightly less than magnesium but in Shadow Lake sodium concentrations are about half of magnesium concentrations. The higher amounts of Na in Mirror Lake probably indicates a greater impact of the application of road salt in the watershed. Chloride concentrations are also much higher in Mirror Lake. Both Na and Cl concentrations decreased in both lakes between 1978 and 1981. This can be attributed to the diversion of the storm sewers. Elevated levels of sulfate as a result of the alum treatment are being slowly flushed out of both lakes although at a faster rate in Shadow Lake because of its shorter hydraulic retention time. Dissolved silica concentrations were higher in the bottom waters partly because of dissolution of diatom frustules, but more importantly because of sediment release of silica. Kamp-Nielsen (1974) noted that SiO_2 was released from sediments during anaerobic conditions.

Conductivity values for 1977 are presented in Figures 22a and 22b. These values and trends have remained relatively unchanged throughout the course of the study. Mirror Lake generally exhibited higher values than Shadow Lake, mostly because of increased levels of calcium and bicarbonate. Seasonal minimums were exhibited during July-September as a result of biogenic precipitation of calcium carbonate. Maximum values occurred in the bottom waters during anaerobic periods as a result of sediment release and transport from the epilimnion.

Total alkalinity values generally are somewhat higher in Mirror Lake than Shadow Lake, ranging from 145 mg/l to 215 mg/l, whereas Shadow Lake ranged from 125 mg/l to 190 mg/l (Figures 23 and 24). The range of pH values is similar for both lakes being 7.1 to 8.8. The values for Mirror Lake are only for the water column above 8 meters. Alkalinity values would be expected to be higher at deeper depths during the summer stratified period.

Both lakes thermally stratify during the summer from May to November. Since the fall of 1977, Mirror Lake has been dimictic because of artificial circulation, while Shadow Lake completely mixes in the fall, but not necessarily in the spring. When holomixis does occur for Shadow Lake in the spring, it often is only brief (Figure 25). During this study period, Shadow Lake only mixed completely in the spring of 1977 and 1978. The maximum surface temperatures usually occurred in July and were about 26°C. The thermocline usually began around 3 to 4 meters in both lakes, but it did move deeper as the surface waters cooled in late summer.

Table 7. Selected Chemical Parameters from Mirror and Shadow Lakes. Units are mg/l.

	Mirror Lake													
Depth	Ca		Mg		Na		K		Cl		SO_4		SiO_2	
	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81
0	43	28	27	27	24	22	5.3	5	51	45	38	33	--	3.1
2	41	29	28	27	24	21	5.4	5	52	44	38	34	--	3.2
4	41	28	27	27	24	21	5.5	5	51	45	36	33	--	3.2
6	41	45	27	27	24	22	5.3	5	51	47	38	36	--	5.2
8	43	47	--	17	24	22	5.3	5	51	46	41	33	--	6.0
10	52	47	29	27	26	22	5.7	5	55	46	40	36	--	7.4
12	--	52	32	27	34	22	6.1	5	75	44	30	32	--	12.0
13	69	53	31	27	36	22	6.2	6	79	42	30	32	--	13.0
Wt. Mean				27				5	53	45				

	Shadow Lake													
Depth	Ca		Mg		Na		K		Cl		SO_4		SiO_2	
	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81	10-9-78	9-2-81
0	32	23	23	24	12	9	2.4	2	22	14	30	21	--	3.7
2	34	23	23	24	12	9	2.3	2	22	14	30	21	--	3.6
4	34	24	23	24	12	9	2.3	2	22	14	29	21	--	3.8
6	34	36	20	24	12	10	2.2	2	21	15	30	20	--	3.7
8	75	45	24	24	12	10	2.3	2	22	15	24	20	--	8.4
10	44	53	24	25	13	10	2.5	3	23	15	19	21	--	13
12	46	56	25	25	13	10	2.5	3	22	15	19	22	--	14
Wt. Mean				24	12			2	22					

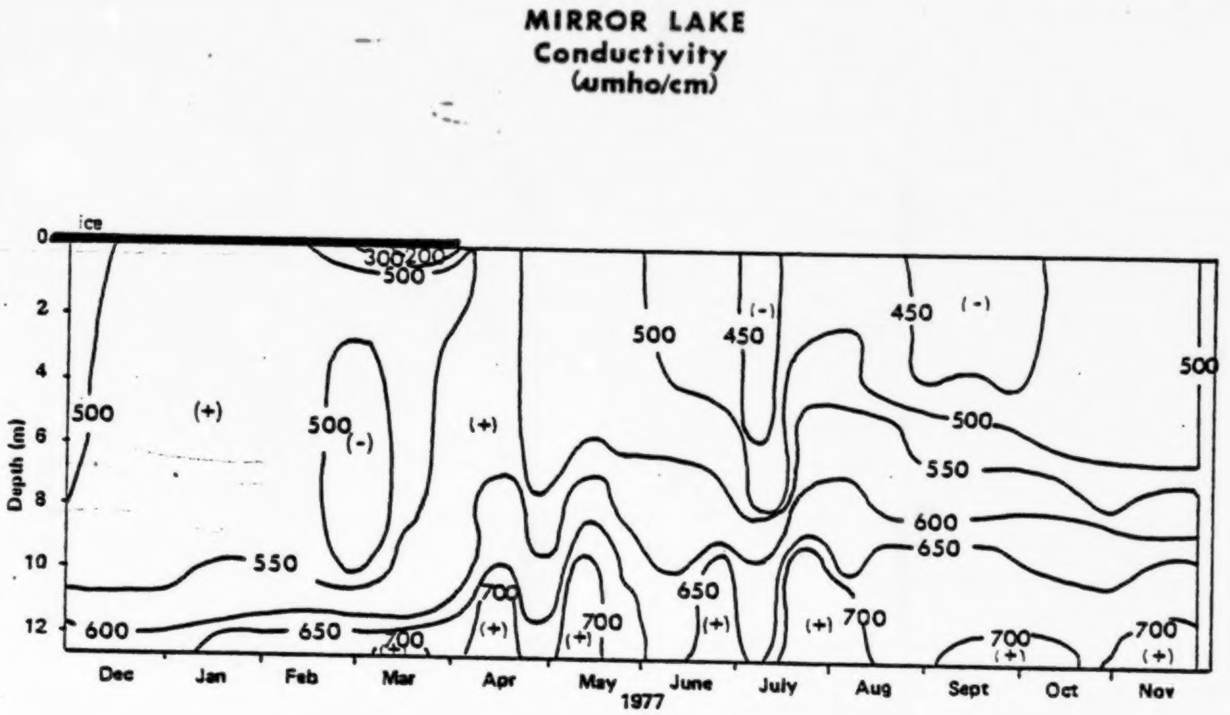
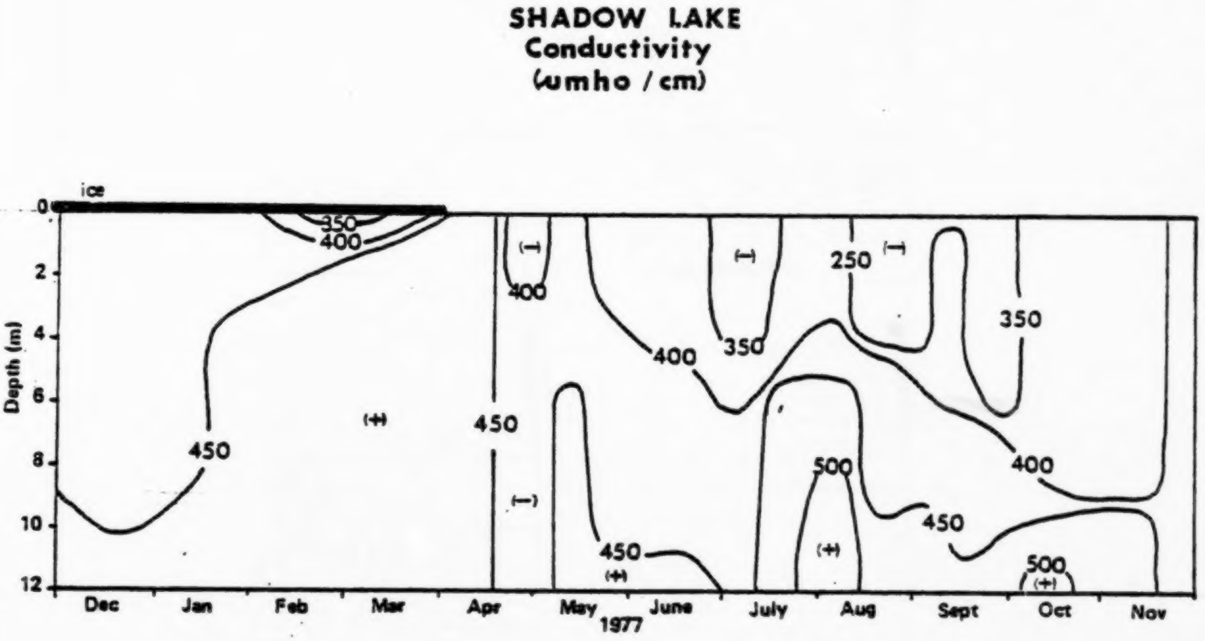


Figure 22. Conductivity isopleths in Mirror and Shadow Lakes.



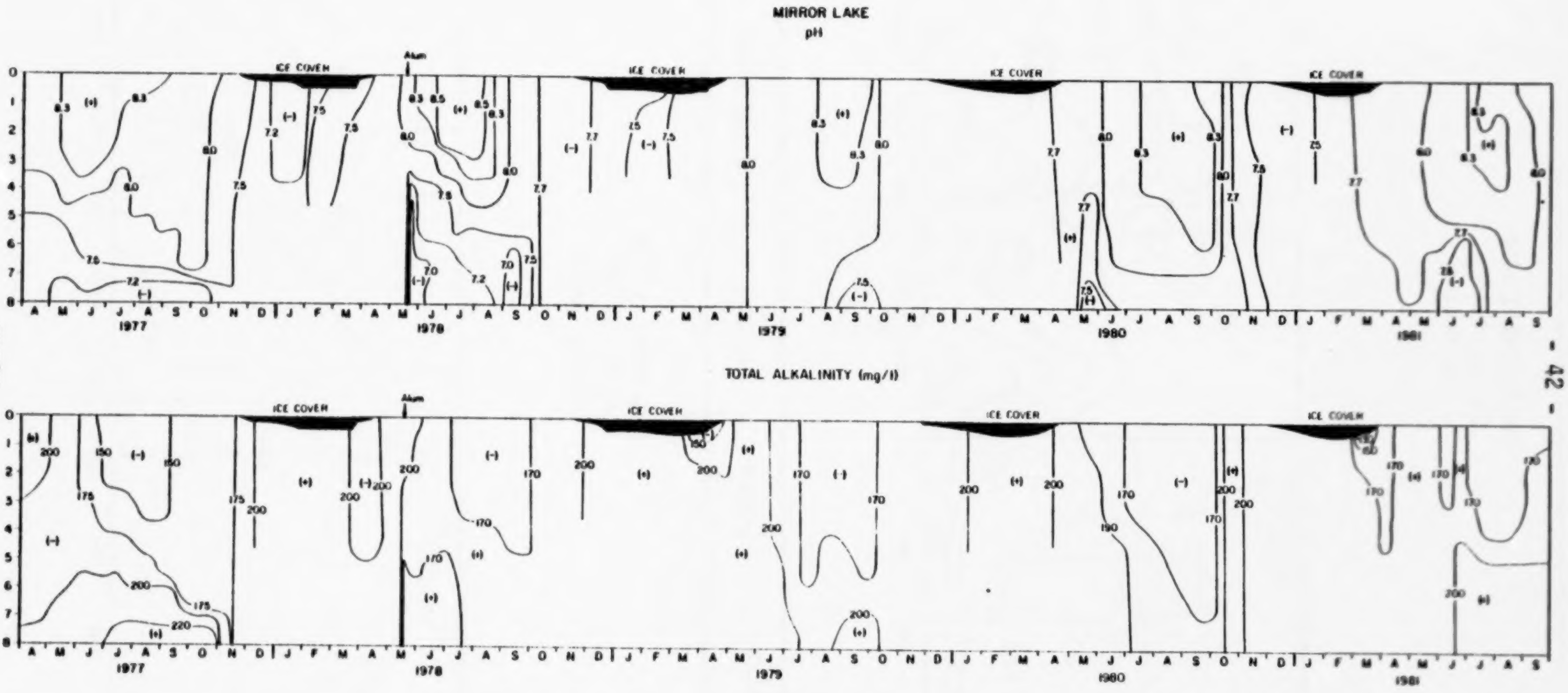


Figure 23. Alkalinity and pH isopleths for Mirror Lake.

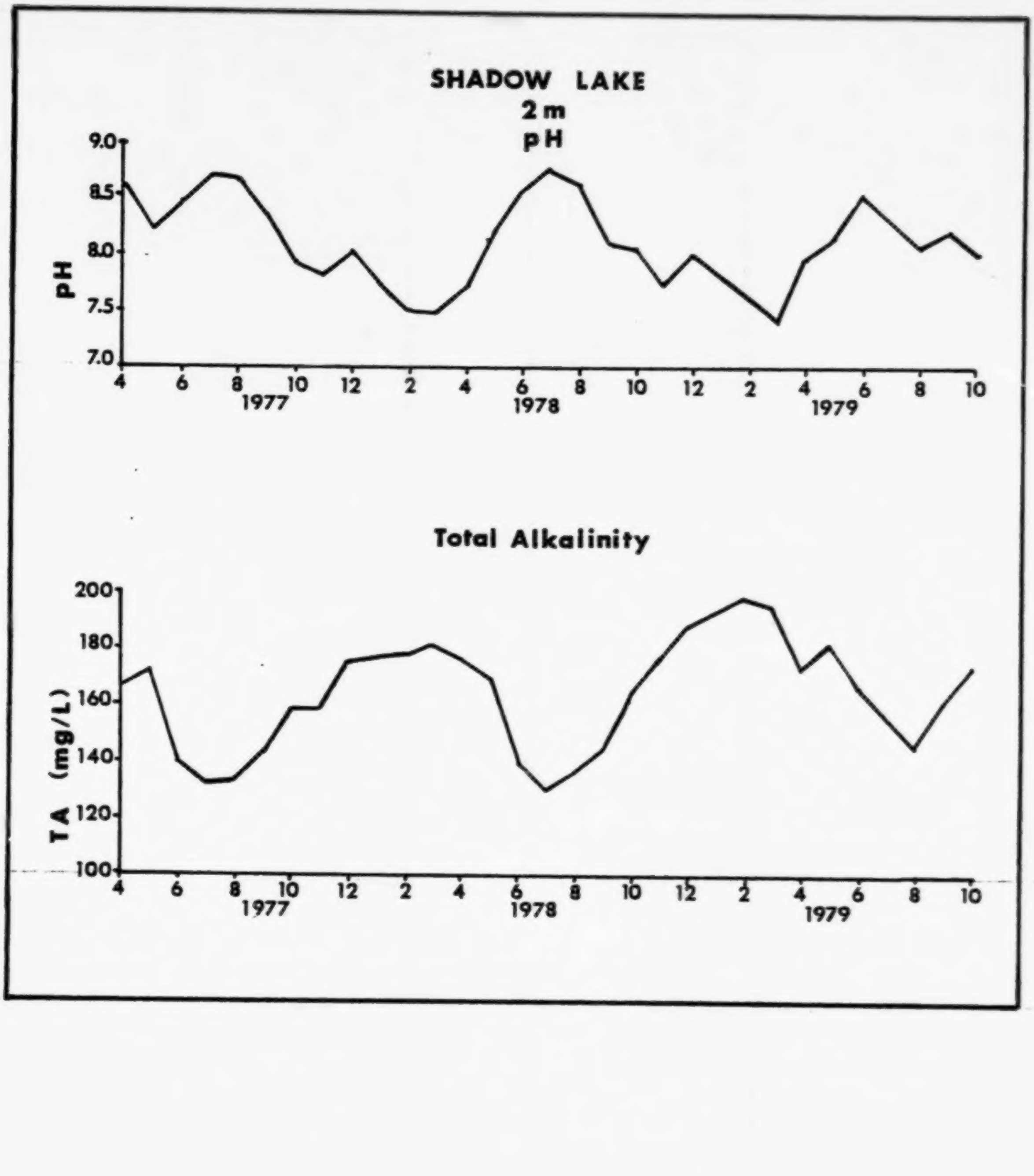


Figure 24. Alkalinity and pH for Shadow Lake, 1977-1979.

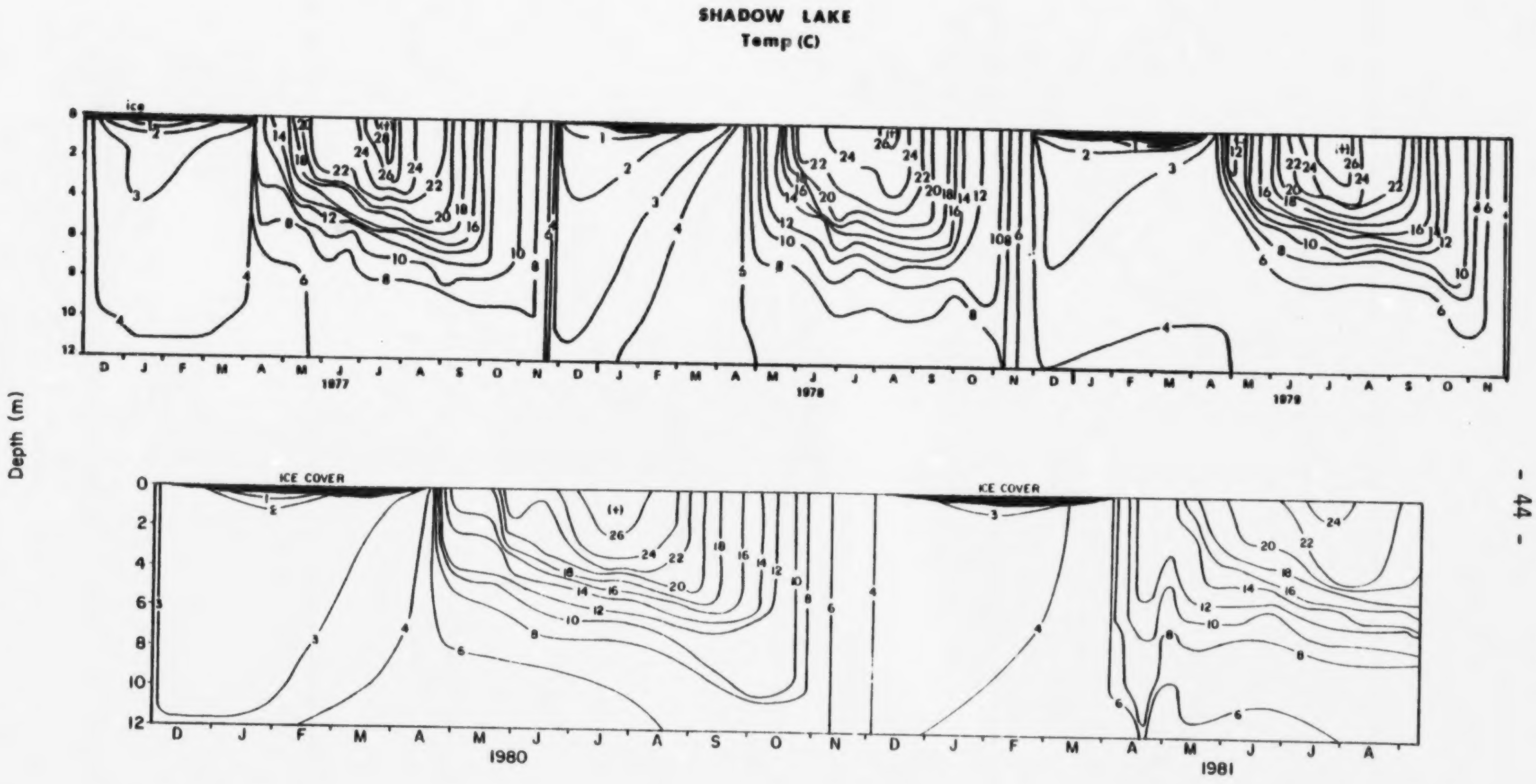


Figure 25. Isotherms for Shadow Lakes.

Mirror Lake exhibits a significant metalimnetic oxygen maximum during periods of stratification (Figure 9). In 1977, 1978, and 1979, the maxima exceeded 20 mg/l. In 1980, the metalimnetic oxygen maximum did not exceed 16 mg/l. The depth of the maxima varies from year to year. Shadow Lake also exhibits metalimnetic oxygen maxima during periods of summer stratification. The maximum dissolved oxygen concentrations generally were less than for Mirror Lake, however the maximum concentrations have progressively increased since 1977. Eberly (1964) observed that lakes which contain a large metalimnetic bloom of the blue green alga Oscillatoria often have metalimnetic oxygen maxima which he attributed to oxygen produced by photosynthesis. Although both lakes often contained a large population of this alga, it probably is not responsible for the maxima. The oxygen concentration in the algal layer usually is less than 5 mg/l. More likely the maxima are a result of photosynthesis by algae higher in the metalimnion.

The delineation of the anaerobic zone during summer stratification is determined, to a large degree, by the maximum depth of photosynthetic activity. The lower limit of light availability is usually determined by a hypolimnetic algal layer in both lakes. Typically, dissolved oxygen concentrations decrease from 4 - 6 mg/l in this algal layer to 0 mg/l immediately below it, a change in depth of about one meter. In Mirror Lake during 1977, the depth of the anaerobic zone begins at 7.5 meters, but following the alum treatment in May, 1978, the anaerobic zone began at 8.5 meters. This was a result of increased water clarity, allowing photosynthetic oxygen production to occur at a greater depth. During July 1979 the depth of the anaerobic zone began at 10 m. With decreased water clarity in the surface waters in later summer, the level moved upward to 8 m in August and September. In 1980 and 1981, the top of the anaerobic zone was at 9 m for most of the summer.

In Shadow Lake during 1977 and 1978, the depth at which the anaerobic zone began was 9 m, but in the latter part of the summer, this level moved upward one meter (Figure 26). Although the surface waters were more transparent in 1979, the deep algal layer was more concentrated, limiting the maximum depth of photosynthetic activity. During the later part of summer stratification in 1979 (August-October), the depth at which the anaerobic zone began was at 8 m. In 1980, the level steadily moved up during the summer from 9.5 m in June to 7.5 m in September.

Spring total phosphorus concentrations have been greatly reduced since the alum treatment (Figure 27 and 28). The summer epilimnetic concentrations are similar to the values experienced on 1977 prior to the alum treatment. The blue green alga Oscillatoria agardhii, prior to the alum treatment, reached bloom proportions at about the time of ice-out in the spring. As the population of this alga increased, it appeared to assimilate the available inorganic phosphorus (Figure 18 and 19) and most of the inorganic nitrogen. As the surface waters warmed, the O. agardhii standing crop moved to deeper depths and as a result, the epilimnion was scavenged of much of its phosphorus. Since the diversion of the storm sewers there has been little external phosphorus loading and the epilimnetic waters have maintained phosphorus concentrations of 20 ug/l or less. Phosphorus concentrations prior to 1978 were not reported by the Water Chemistry Lab of less than 20 ug/l, so concentrations in the surface waters are not necessarily lower following the alum treatment.

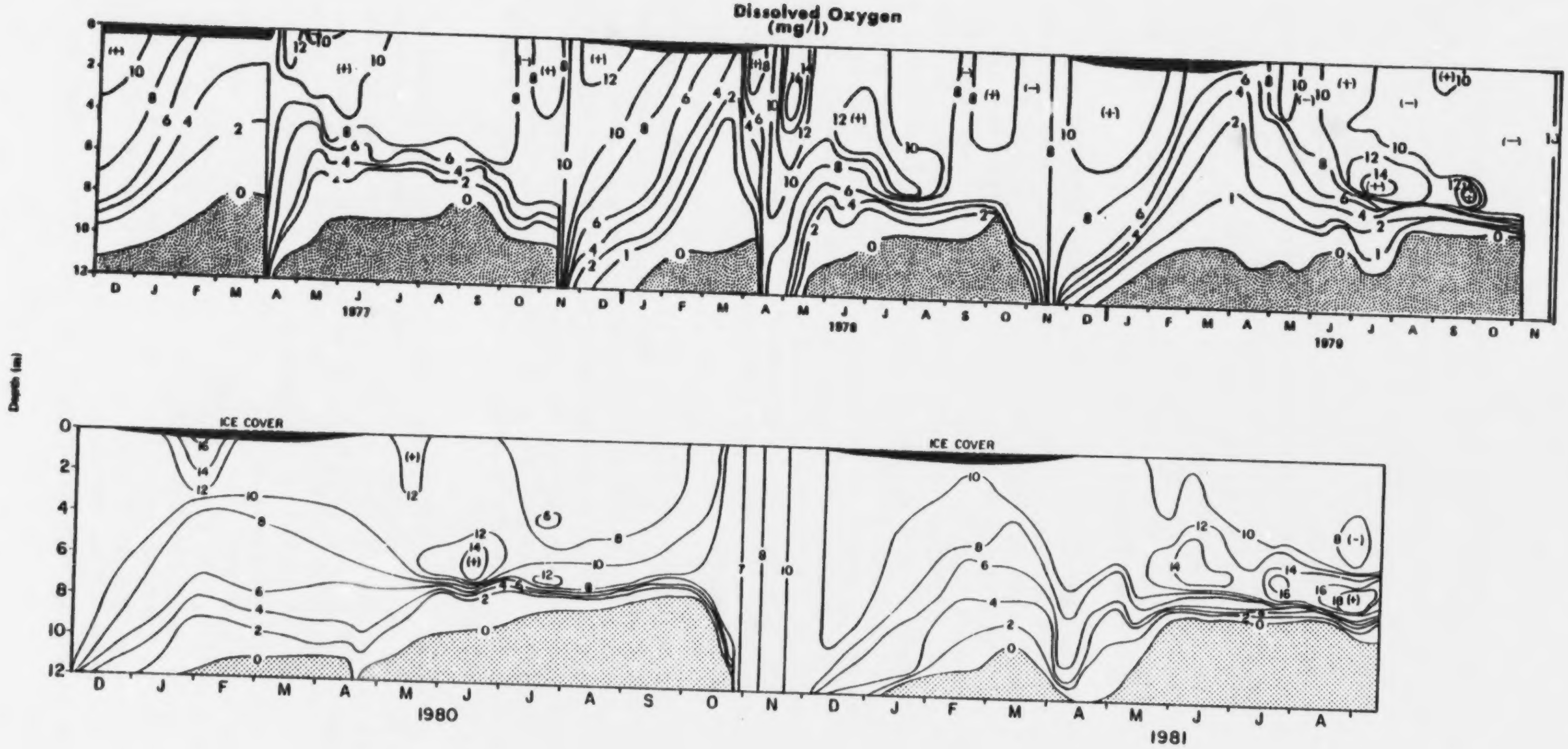


Figure 26. Dissolved oxygen isopleths for Shadow Lake.

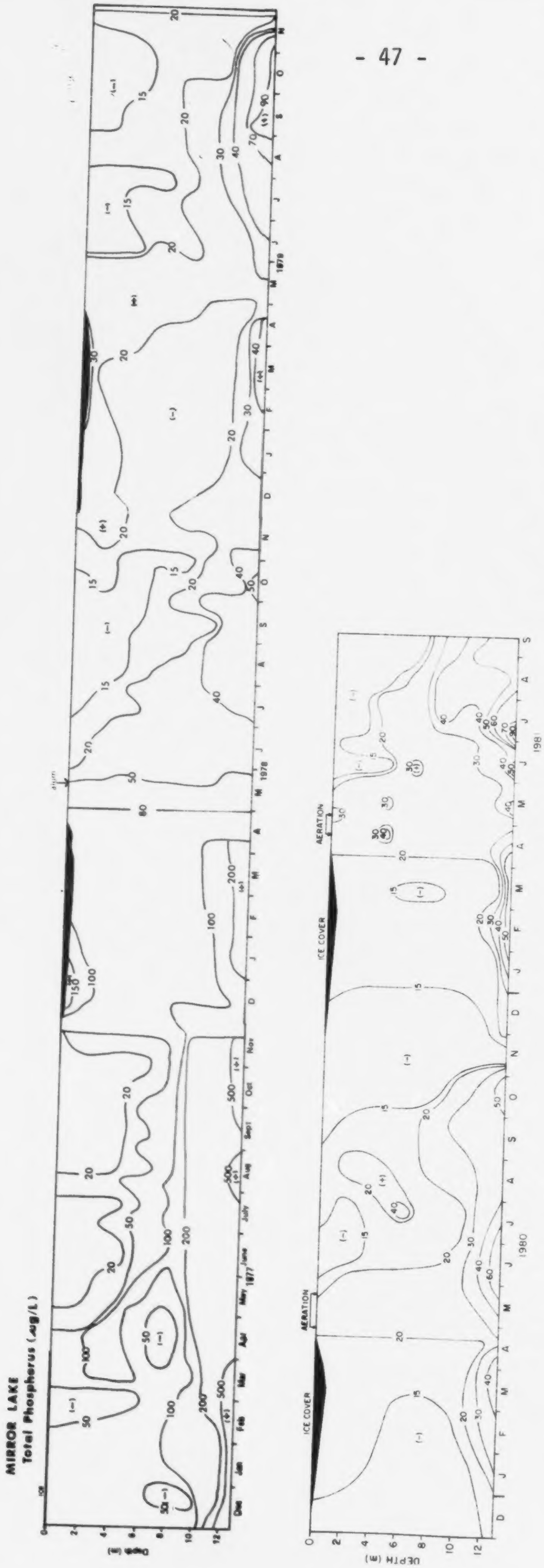


Figure 27. Total phosphorus isopleths for Mirror Lake.

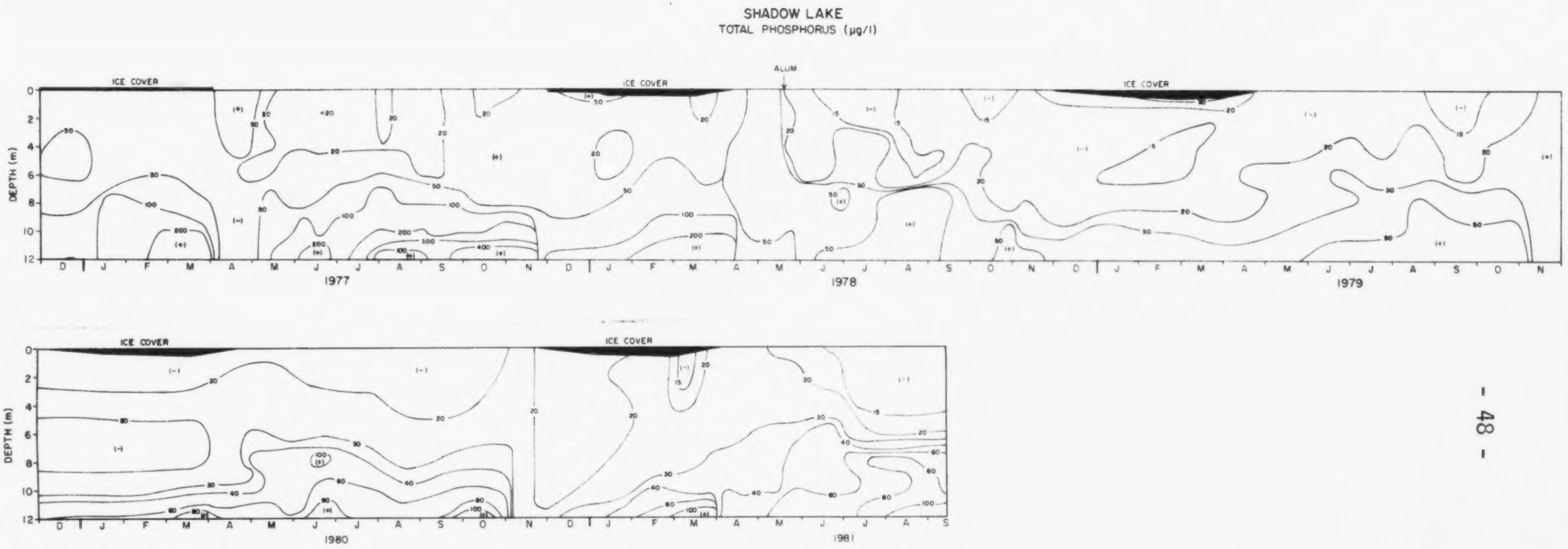


Figure 28. Total phosphorus isopleths for Shadow Lake.

Prior to the alum treatment, total phosphorus concentrations in the bottom waters exceeded 500 ug/l in Mirror Lake and 400 ug/l in Shadow Lake. Most of this phosphorus probably orginated from the sediments as over 75 percent and 60 percent of this phosphorus was present in the inorganic form in Mirror and Shadow Lakes, respectively. This is the chemical form of phosphorus that would diffuse from the bottom sediments.

The nitrogen concentrations were relatively unchanged during the course of the study with some temporary fluctuations. Typically, nitrogen was highest during the ice-covered period when biological utilization was low and decreased during the spring and early summer with increased algal production and subsequent sedimentation. As ammonium was released from the sediments during anaerobic conditions, the nitrogen content in the lakes increased during summer and early fall.

In Mirror Lake, nitrate-N was usually highest during the winter except during the winter of 1977-1978 (Figure 29). During this winter, oxygen concentrations were very low. This probably resulted in bacterial denitrification which reduced NO_3 to N_2. This same reduction process probably occurs in the hypolimnion during stratification. Normally nitrate concentrations proceeded from very low levels in the fall and steadily increased during ice cover with the nitrification of ammonium, to a peak in March. With increased algal production, the nitrate levels began to decline until they were undetectable by August. In 1977, NO_3-N levels were undetectable very soon following ice-out. This was possibly a result of the rapid incorporation by a bloom of Oscillatoria agardhii var. This alga rapidly utilizes both inorganic nitrogen and phosphorus.

In Shadow Lake, nitrate-N exhibited seasonal distribution (Figure 28) similar to Mirror Lake. The nitrate concentrations were highest during the winter and steadily declined following ice-out until it was undetectable by July. Nitrate-N generally was undetectable about one month earlier in Shadow Lake than Mirror Lake, although winter concentrations reached similar levels.

Contrary to the seasonal trend with nitrate-N, ammonium-N declined during the winter months in both lakes (Figures 31 and 32). This was probably caused by the bacterially mediated process of nitrification converting ammonium to nitrate. Generally by ice-out, the ammonium-N concentration was less than 0.10 mg/l. As with nitrate-N, the ammonium-N concentration rapidly declined and often was undetectable in the upper 8 m in Mirror Lake and the upper 6 m in Shadow Lake.

In the spring of 1978 in Mirror Lake, ammonium-N concentrations were higher than normal because the nitrification process appeared to be inhibited the previous winter because of low oxygen levels. Ammonium-N concentrations still declined rapidly and were undetectable by July.

With the onset of anaerobic conditions during summer stratification and during ice cover, ammonium levels began to increase in the bottom waters. This increase was probably due to the release of ammonium from the sediments with the destruction of the oxidized microzone, in a process similar to the release of phosphate. Mortimer (1941 and 1942) and Kamp-Nielsen (1974) noted that

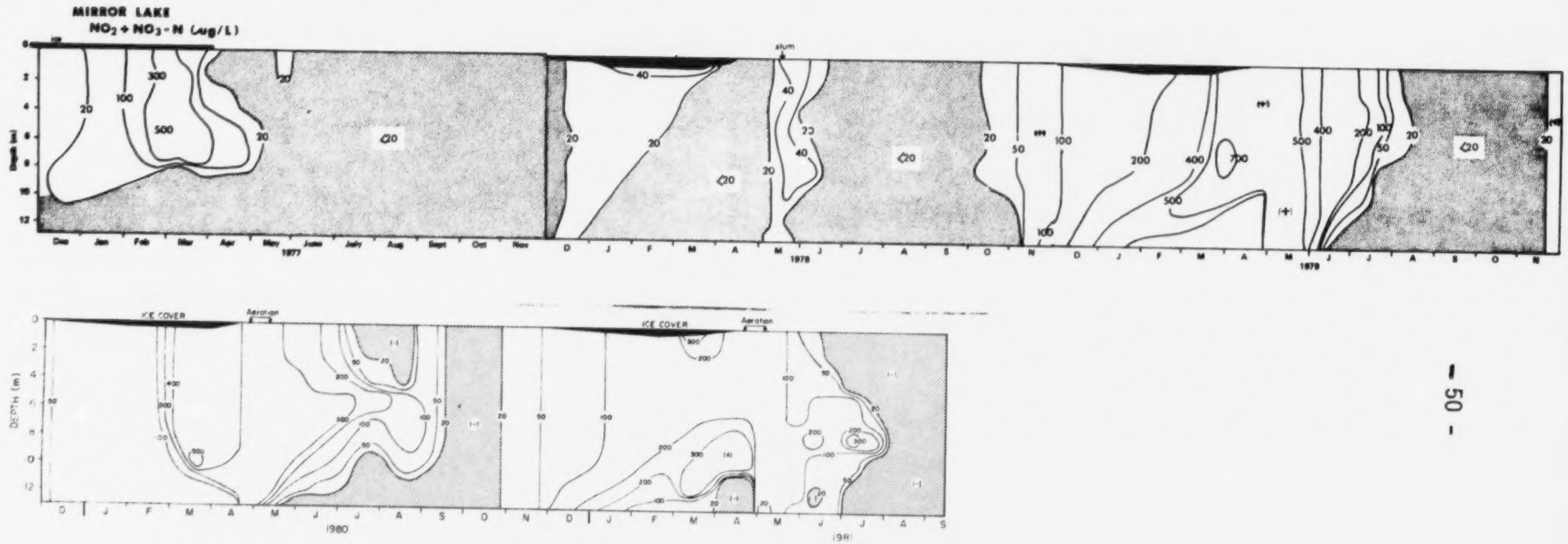


Figure 29. Nitrate isopleths for Mirror Lake.

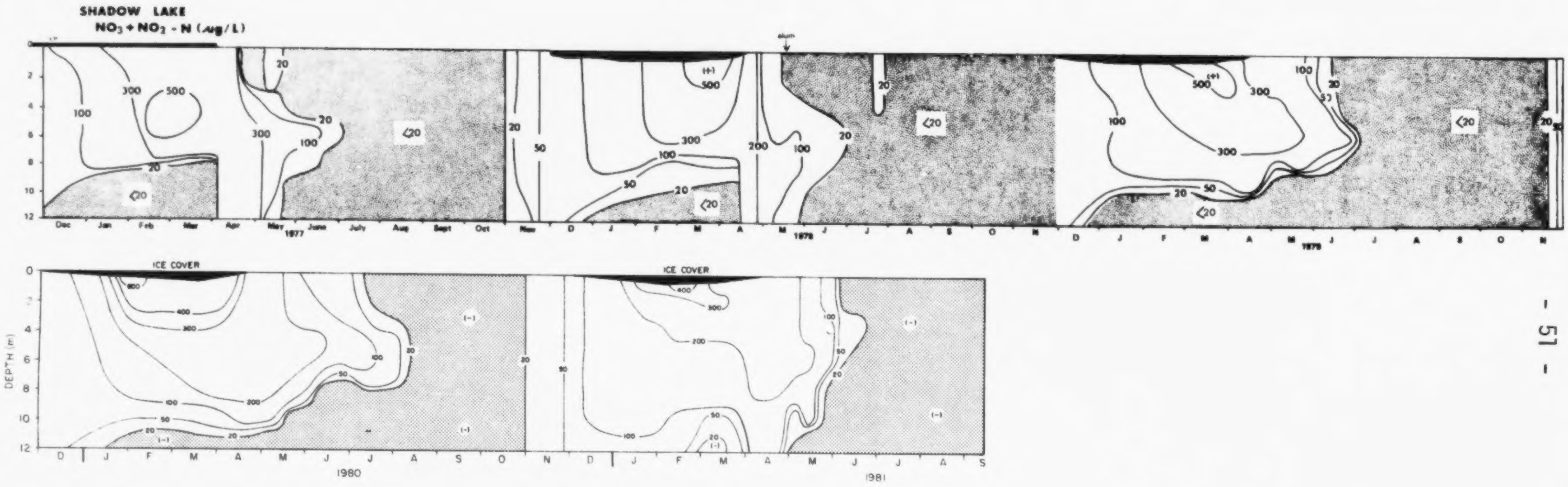


Figure 30. Nitrate isopleths for Shadow Lake.

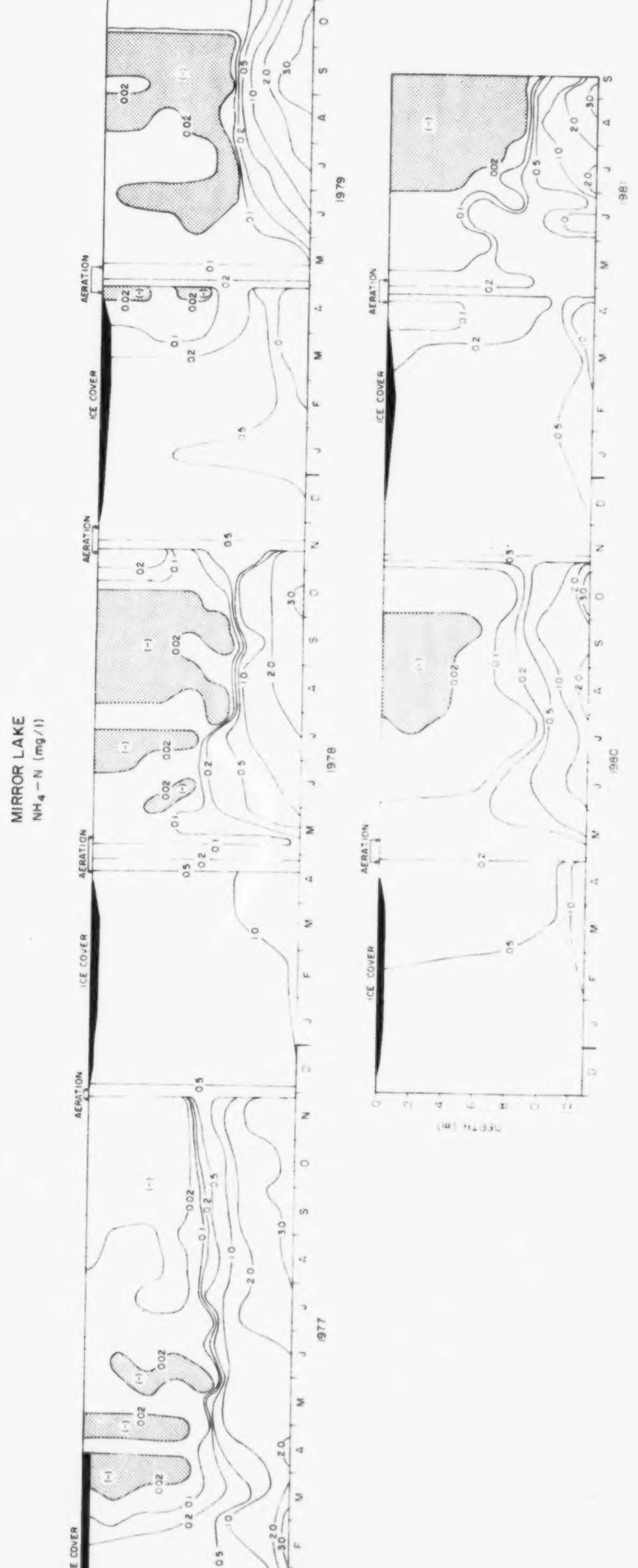


Figure 31. Ammonium isopleths for Mirror Lake.

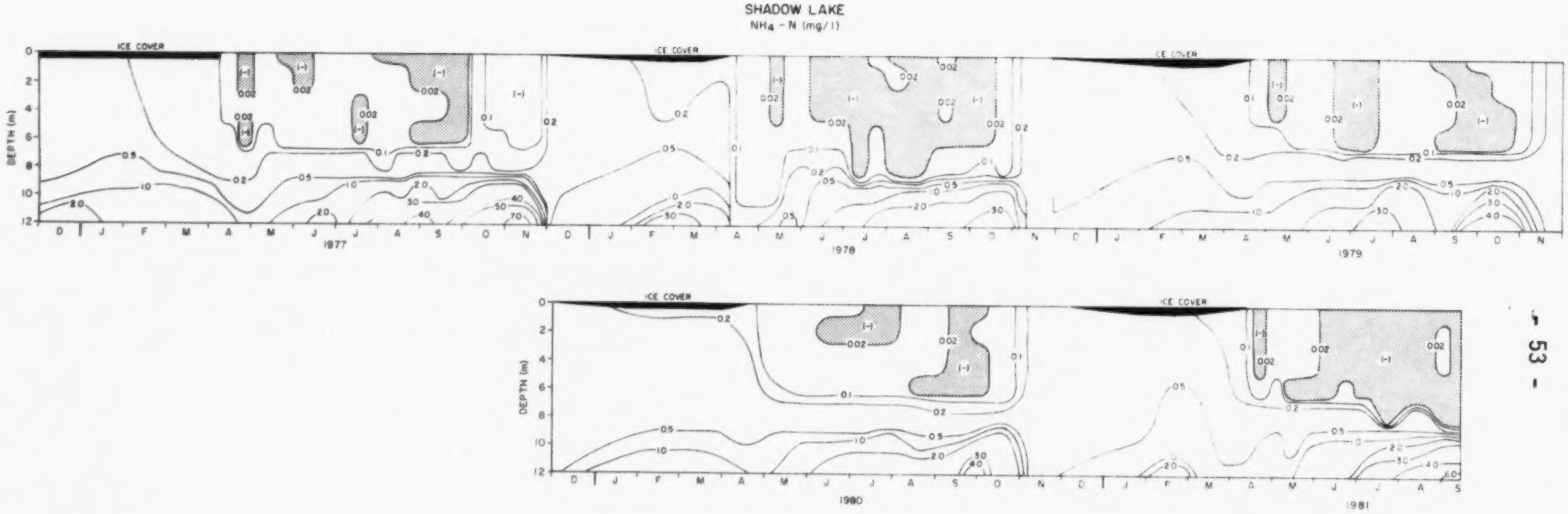


Figure 32. Ammonium isopleths for Shadow Lake.

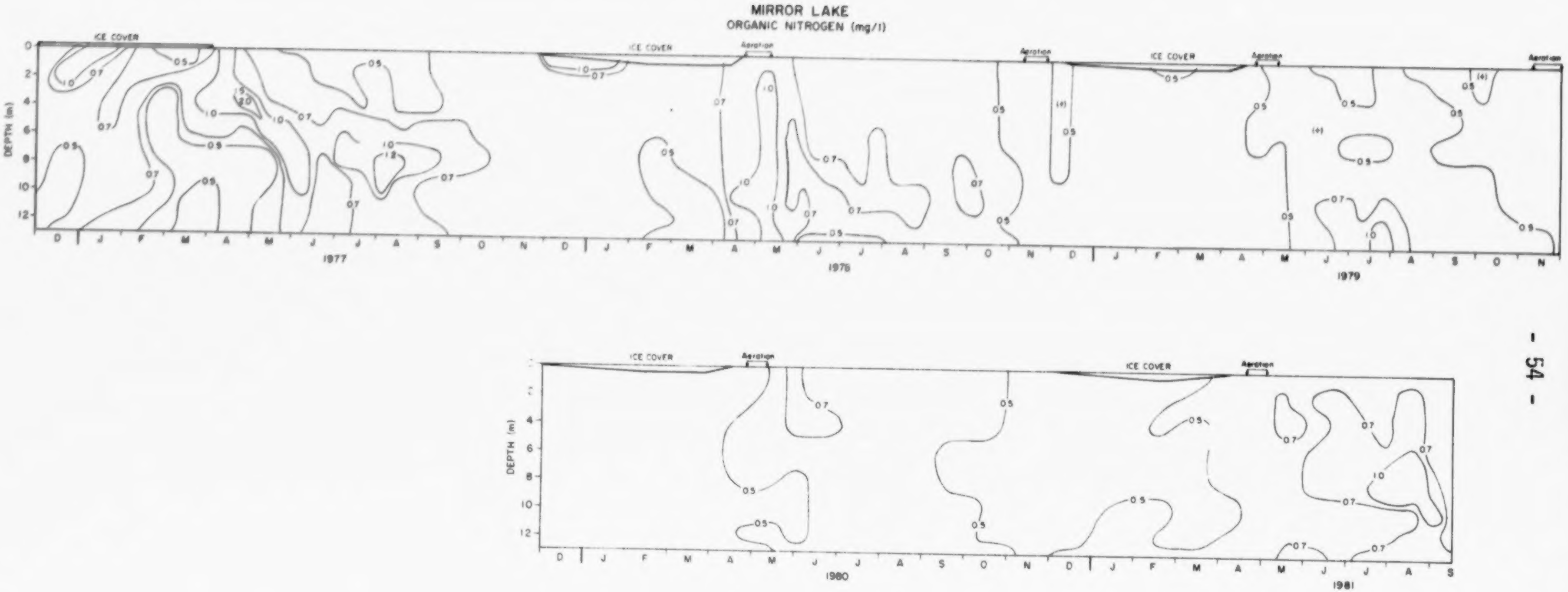


Figure 33. Organic-nitrogen isopleths for Mirror Lake.

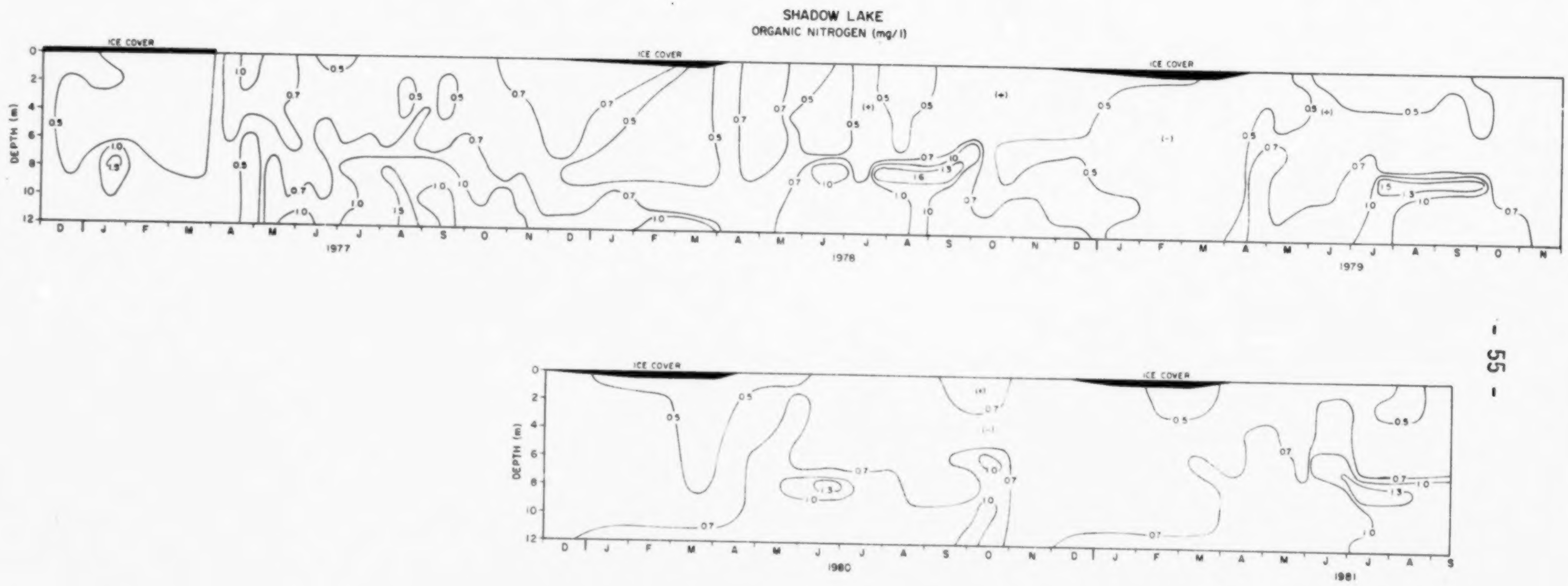


Figure 34. Organic-nitrogen isopleths for Shadow Lake.

ammonium was released during anaerobic conditions. Concentrations in the bottom waters often exceeded 3 mg/l in Mirror Lake during summer stratification and were greater than 4 mg/l in Shadow Lake. When the lakes mixed in the fall, ammonium was distributed throughout the lake and underwent nitrification during the winter. During spring and early summer, the inorganic nitrogen (NH_4-N and NO_2 + NO_3-N) was biologically combined with some of the resultant organic nitrogen returning to the sediments. The sediments in both lakes then are truly providing much of the nitrogen which drives the algal production. The fact that hypolimnetic nitrogen levels have not declined since the storm sewer diversion (which would be expected to retard sediment ammonium release) indicates that the phosphorus concentrations may have been similar to prediversion levels if the lakes were not treated with alum.

Figures 33 and 34 show organic nitrogen isopleths for Mirror Lake and Shadow Lake, respectively. The concentrations were generally highest in the metalimnion during summer stratification in both lakes. This was due to the large algal population present, dominated by _Oscillatoria agardhii_.

In the springs of 1977 and 1978, organic nitrogen was high in Mirror lake, again as a result of a large population of _O. agardhii_. The sedimentation of this population can be traced by the 1.0 mg/l organic nitrogen isopleth in May and early June. Organic nitrogen concentrations were low in the epiliminion during the study reflecting the low algal populations.

Phosphorus concentrations were greatly reduced in Horseshoe Lake, Wisconsin following alum treatment (Peterson et al. 1973), however, the concentrations in the bottom waters continually increased each year following the alum treatment (Born 1979). This was thought to result not from increasing release of phosphorus from the sediments beneath the alum layer, but instead from sedimenting particulate matter. Since the major nutrient sources were not diverted, epilimnetic production continued to be substantial.

Figure 35 shows the daily photosynthetic rate and daily carbon sedimentation rate for the ice-free period of 1978 and 1979 and part of 1981. The amount of carbon collected in the traps was measured directly in 1978. In 1979 and 1981, carbon was not measured directly, but estimated from volatile suspended solid concentrations. From data collected in 1978, a regression equation,

$$C = 0.48\ VSS + 2.10\ (n = 12,\ r^2 = 0.92)$$

was calculated to estimate organic carbon concentration. The high sedimentation rate in mid-May 1978 was the result of the alum treatment as the alum floc removed some of the particulate matter from the water column. This increased sedimentation rate also was evident with phosphorus and nitrogen (Figure 36).

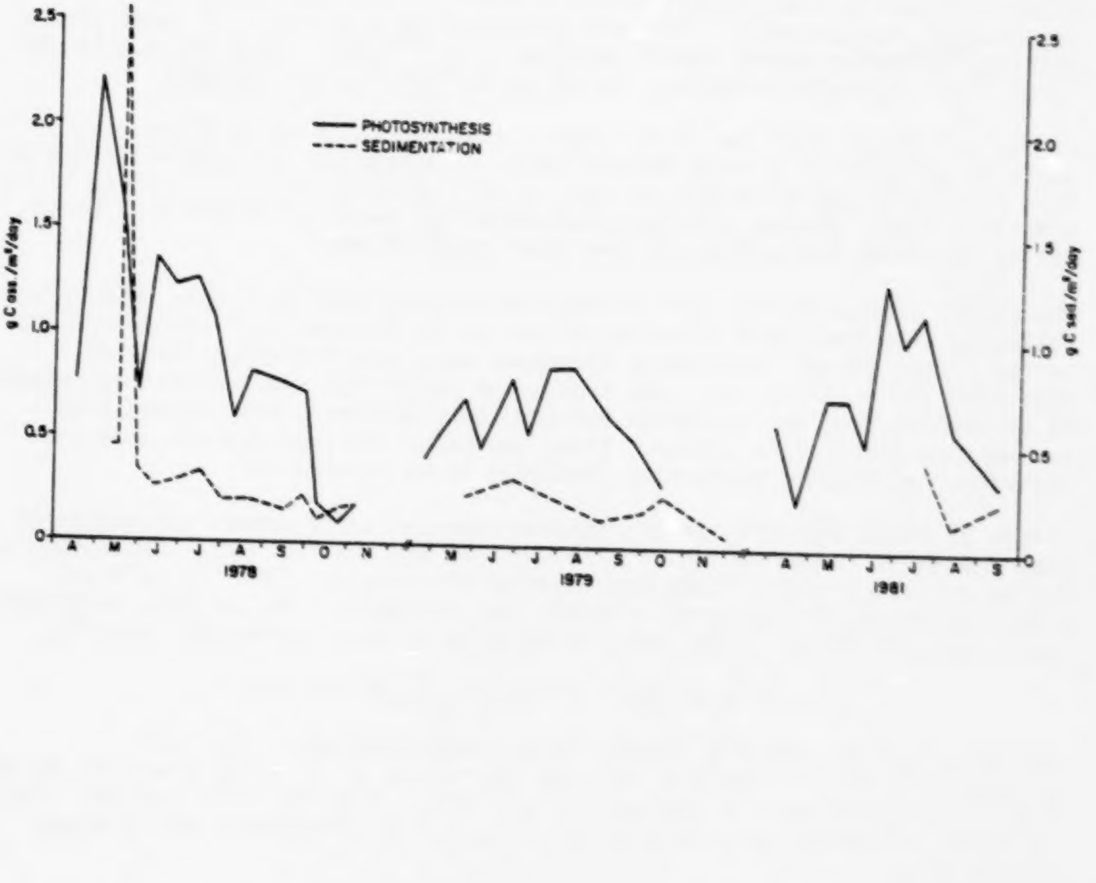


Figure 35. Algal productivity and carbon sedimentation for Mirror Lake.

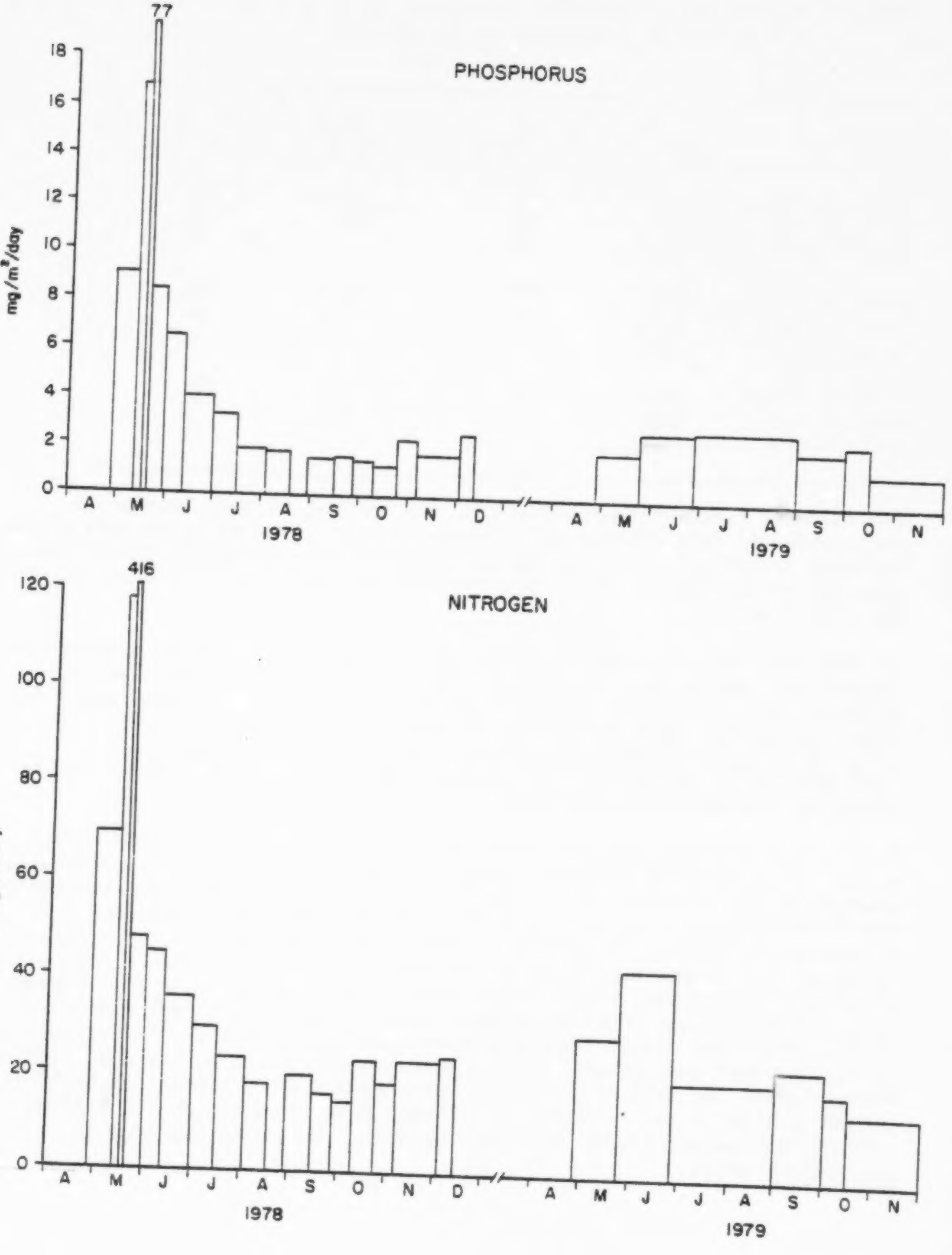


Figure 36. Phosphorus and nitrogen sedimentation for Mirror Lake.

Table 8 Particulate production, sedimentation, and accumulation of carbon, nitrogen, and phosphorus in Mirror Lake.

	1978 1 May - 28 Nov		1979 22 April - 28 Nov	
	g/m^2	% of Prod.	g/m^2	% of Prod.
Part. C. Prod.	177	100	125	100
Part. C. Sed.	54	30	40	32
Accumulation	32	18	--	--
Part. N. Prod.	29.5	100	20.8	100
Part. N. Sed.	7.2	24	5.2	25
Accumulation	2.2	7	--	--
Part. P. Prod.	4.3	100	3.0	100
Part. P. Sed.	0.9	21	0.4	13
Accumulation	0.7	16	--	--

The seasonal trend in carbon sedimentation did not closely follow the photosynthetic rate (Figure 35). Phosphorus and nitrogen rates more closely followed carbon assimilation, being highest in the spring of 1978 (Figure 36) when the production was high, but lower in the spring of 1979 when production was also lower.

In 1978 and 1979 only, 30-32 percent of the carbon produced by photosynthesis reached the sediments. This agrees with the amount of photosynthetically produced carbon reaching the sediments in other studies. Kimmel and Goldman (1977) noted that 26.6 percent of the particulate carbon production in oligo-mesotrophic Castle Lake reached the bottom, and in eutrophic Lake Mendota, 31 percent of the photosynthetically produced carbon reached the sediments (Fallon and Brock 1980).

Particulate nitrogen and phosphorus production was estimated from carbon uptake rates assuming nitrogen production was one-sixth that of carbon and phosphorus was one-forty first (Redfield et al. 1963). Nitrogen sedimentation was 24-25 percent of production both years, but phosphorus declined from 21 percent in 1978 to 13 percent in 1979. The small percentage of carbon, nitrogen, and phosphorus reaching the sediments indicates that a high degree of mineralization took place in the water column, probably in the trophogenic zone. Although many previous workers (e.g. Kajack et al. 1972 and Wetzel et al. 1972) have stated that most mineralization occurs in the epilimnion. It appears that most mineralization does not take place in the hypoilimnion in Mirror Lake. The data from the nutrient regeneration chambers indicate that enough phosphorus and nitrogen is released from the sediments in 1977 to achieve the concentrations that were present. This also was true in the succeeding years.

Decomposition at the sediment surface was estimated by comparing average C, N, and P composition of the upper sediments with that of the sedimented material collected in the traps. Forty-one percent of the carbon, 69 percent of the nitrogen, and 22 percent of the phosphorus which reached the sediment surface was mineralized between the time of initial deposition and permanent burial in the sediments.

Since 80-85 percent of the phosphorus produced in the euphotic zone appears to be eventually mineralized before it is buried in the sediments, it becomes very important to reduce major external nutrient sources. If the algal production is reduced, the total phosphorus mineralization is also reduced. With a reduction in primary production in 1979, both phosphorus and nitrogen exhibited reduced sedimentation rates. The inlake phosphorus concentration in 1979 was also less than in 1978. With the reduced phosphorus concentrations, competition increased for the available phosphorus with the result that a higher percentage of the particulate phosphorus production was mineralized in the water column; 79 percent in 1978, and 87 percent in 1979 (Table 8). The mineralization rate for carbon and nitrogen remained the same both years. This is further evident from the N to P ratio which increased from 8:1 in 1978 to 13:1 in 1979, while the C to N ratio remained at 24:1.

BIOLOGY

Macrophyte maps for Mirror and Shadow Lakes are presented in Figures 37 and 38. The dominant macrophytes in Mirror Lake were *Myriophyllum exalbescens*, *Ceratophyllum demersum*, and to a lesser extent, *Potamogeton pectinatus*, *P. pusciilus* and *Chara* sp. (Sullivan 1977a). The dominant species in Shadow Lake were *Chara* sp. followed by *Potamogeton alpinus*, *P. pectinatus*, and *M. exalbescens* (Sullivan 1977b).

In Mirror Lake, a large portion of the nearshore littoral area consists of a *Myriophyllum-Potamogeton* mixture, while the deepest area is mostly a *C. desmersum* community. The only significant difference between the macrophyte communities in 1977 and 1978 was an increase to the size of the *Chara* community in the southern one-third of the lake.

Most of the nearshore littoral community is dominated by *Chara* in Shadow Lake. The deepest portion is dominated by a mixture of *C. desmersum* and *M. exalbescens*. The macrophyte community was generally similar in 1977 and 1978, with the exception that *C. desmersum* did not grow to as deep a depth in the northwestern corner where the storm sewer at one time emptied into the lake. *Heteranthera dubia* was present in moderate amounts during 1977 but was infrequently encountered in 1978.

Benthic invertebrates were sampled in March for three years to estimate their response to the lake restoration project. Since samples were only collected annually in the deepest portion of the lakes, the reported larvae do not indicate that these are a representative sample of the invertebrates in the lakes. It would be expected that the littoral zone would contain a wide variety of species. Virtually the only organism collected was *Chaoborus punctipennis* in both lakes. One *C. albatus* was collected in Shadow Lake in 1979, and one *Chironomus* sp. was collected in each lake in 1981. The size of

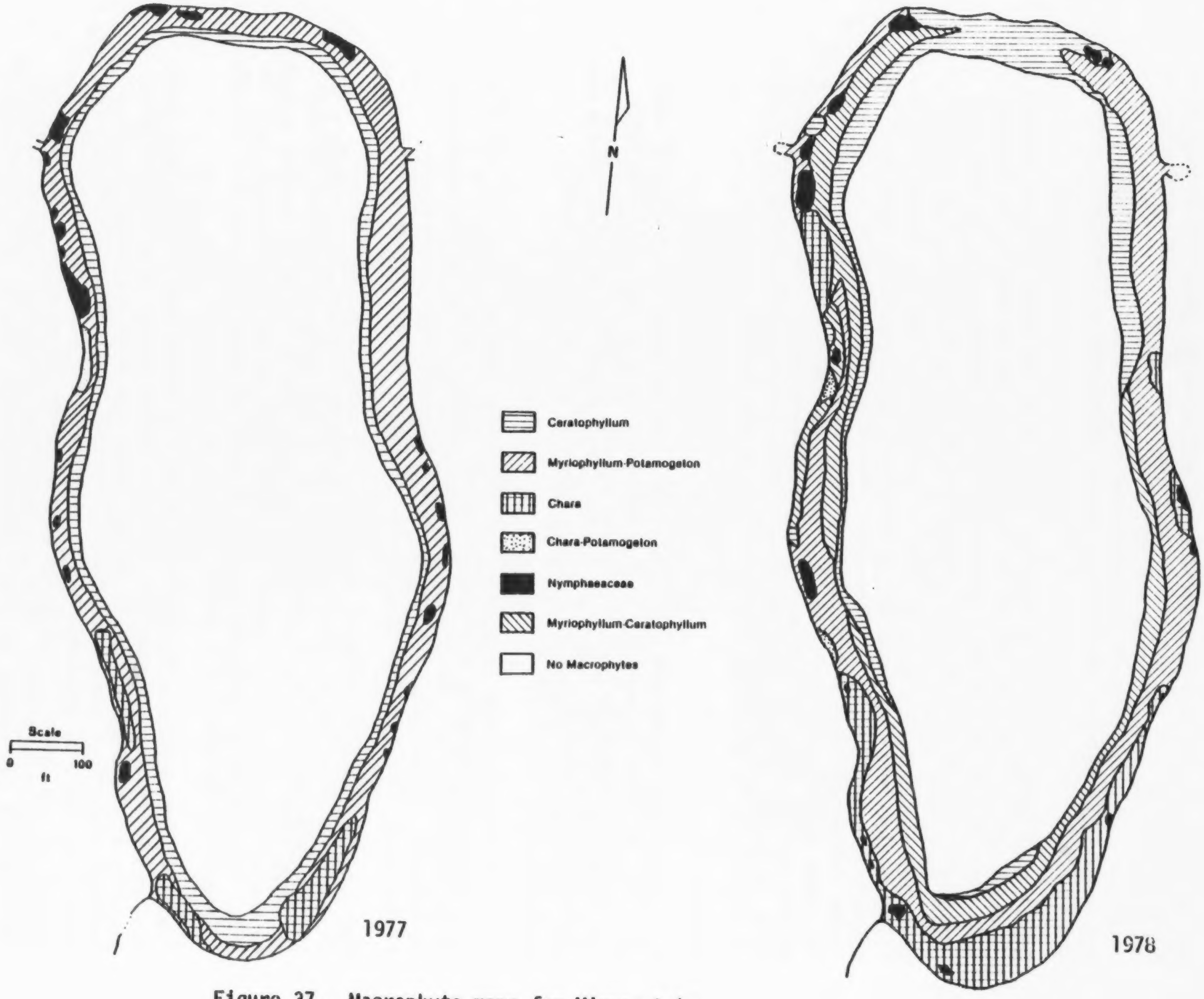
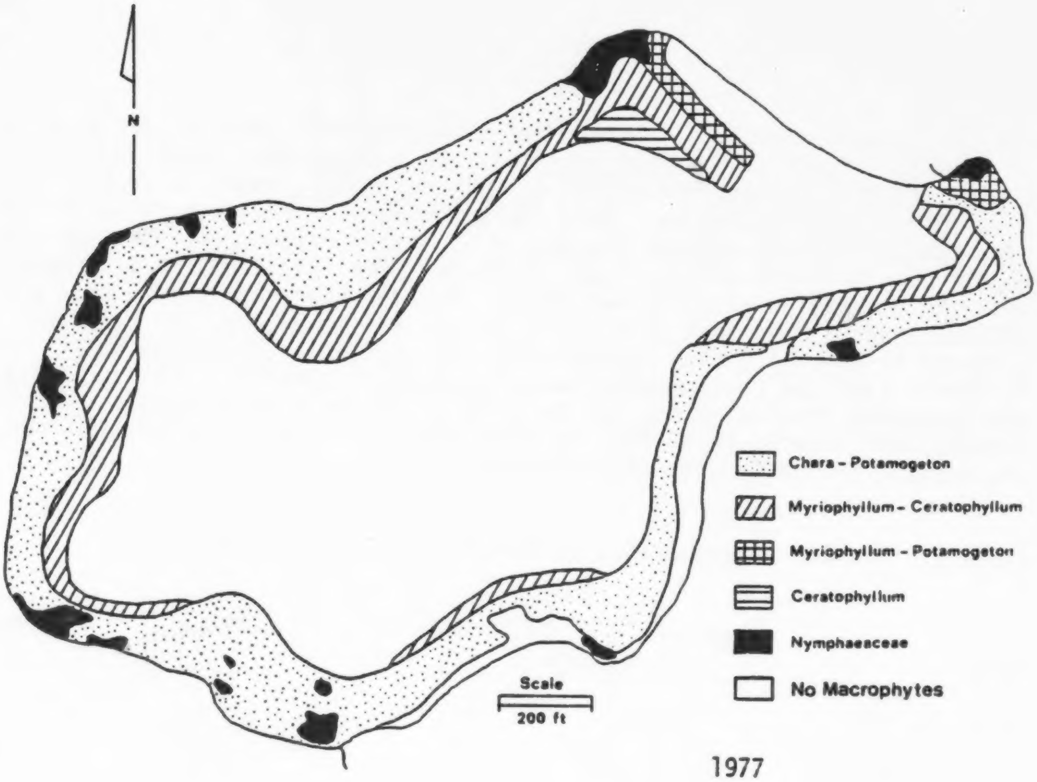
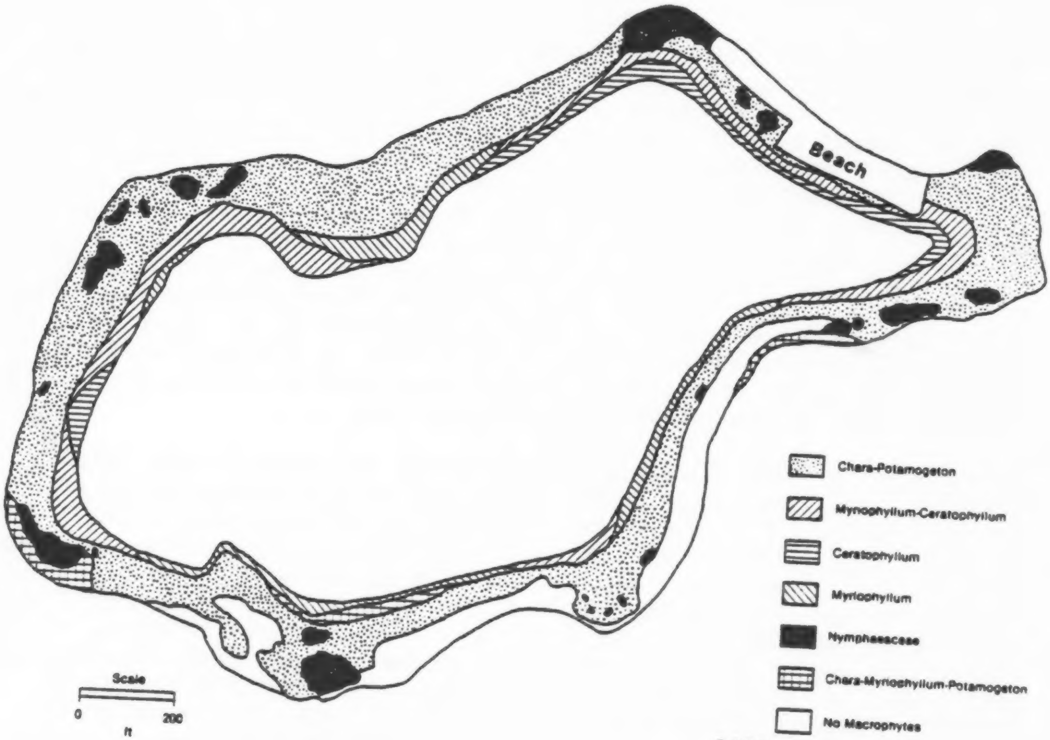

N
Ceratophyllum
Myriophyllum-Potamogeton
Chara
Chara-Potamogeton
Nymphaeaceae
Myriophyllum-Ceratophyllum
No Macrophytes
Scale
0
100
ft
1977
1978

Figure 37. Macrophyte maps for Mirror Lake.


N
Chara - Potamogeton
Myriophyllum - Ceratophyllum
Myriophyllum - Potamogeton
Ceratophyllum
Nymphaeaceae
No Macrophytes
Scale
200 ft

1977


Beach
Chara-Potamogeton
Myriophyllum-Ceratophyllum
Ceratophyllum
Myriophyllum
Nymphaeaceae
Chara-Myriophyllum-Potamogeton
No Macrophytes
Scale
0
200
ft

1973

Figure 38. Macrophyte maps for Shadow Lake.

the *Chaoborus* populations, except Mirror Lake in 1981, were at the lower end of densities found in a survey of 14 Wisconsin Lakes (Hilsenhoff and Narf, 1968). In Mirror Lake, the number of *C. punctipennis* showed a marked increase from 1978 to 1981 (Table 9). This increased density probably reflects the improvement of their habitat because of increased oxygen concentrations, the result of artificial circulation. In Shadow Lake, the opposite trend occurred with the population steadily declining. However, the population density in 1978 was much higher than in Mirror Lake because in Shadow Lake holomixis occurred in the fall, thus replenishing the oxygen in the bottom waters, while in Mirror Lake the bottom waters were constantly anaerobic. The decline in the *Chaoborus* population may not be a result of the alum treatment since Narf (unpublished report) found that in other Wisconsin lakes treated with alum, the benthic community generally improved.

Table 9. Benthic Invertebrates in Mirror and Shadow Lakes.

	Mirror Lake		Shadow Lake	
Date	Chaoborus	Chironomus	Chaoborus	Chironomus
	(Number/m^2)		(Number/m^2)	
16 March 1978	5.4	0	413.0	0
22 March 1979	250.0	0	364.1	0
17 March 1981	2,239.0	5.4	195.6	5.4

Water transparency depends on concentrations of phytoplankton and other light attenuating substances according to the Lambert-Gougher Law for the transmission of light (Megard et al. 1980). Megard et al. (1980) pointed out that the use of a Secchi disc is only valid to estimate changes in algal density when light attenuation caused by chlorophyll (K_c) is greater than attenuation resulting from water and other nonalgal substances (K_u). Using their method in Mirror and Shadow Lakes K_u was generally 0.20. While chlorophyll concentrations were not always large enough to minimize K_u, since K_u was generally constant, Secchi disc measurements should give an indication of changes in algal density. When the epilimnetic waters were very clear, the Secchi depth was more an indication of the upper depth of the larger metalimnetic community than algal density in the surface waters. Although the Secchi measurements do have some inherent errors, they still indicate relative changes in algal standing crop.

Figures 39a, b, show the Secchi depths during the study in both lakes. On a seasonal basis, the lesser Secchi depths are usually during spring mixing in Mirror Lake and during the winter or spring if mixing occurs in Shadow Lake. In Mirror Lake, Secchi depths at spring mixing increased each spring from 1977 through 1980, largely as a result of a decrease in the *Oscillatoria* population. In 1981, spring Secchi depths decreased, but were similar to those experienced in 1978. Generally when stratification develops, the water clears, and summer Secchi depths are in excess of 2.5 m until the metalimnetic algal layer is redistributed in the surface waters during the month of October. However, during August 1979 in Mirror Lake, the Secchi depth decreased to 1.2 m. This was the poorest Secchi depth measured since 1971 when measurements were first made. The increased turbidity did not seem to be a result of increased phytoplankton standing crop as chlorophyll concentrations were only slightly elevated. In Mirror Lake in the summer of 1981 and Shadow Lake in the summer of 1979, Secchi measurements did not show the usual rapid improvement following the onset of stratification, but instead, got progressively better all summer to a maximum in September 1981 of 6.7 m in Mirror Lake and 5.5 meters in Shadow Lake.

The mean and range of summer Secchi disc depths for both lakes are given in Table 10. Mean summer Secchi depths were generally good before storm sewer diversion partially because of the nutrient stripping by the spring Oscillatoria population and partially because there were no heavy rains in the summer. Mean summer Secchi depth was the best in 1978 (4.7 m) probably because of the alum treatment. The alum floc physically entrapped some of the phytoplankton and removed them from the water column. The increase in Secchi depth from 1971 to 1977 in Shadow Lake was probably the result of a 1971 carp eradication program in the Crystal River watershed, of which Mirror and Shadow Lakes are a part. Secchi depths appeared to be reduced in 1981, however, a different observer took the readings using a slightly different method. In actuality, the 1981 Secchi depths were probably similar to those in 1979 and 1980 in Mirror and Shadow Lakes respectively.

Table 9. Summer Secchi Disc Depths in Meters.

		Mirror Lake	Shadow Lake
1971	Mean	3.1	1.8[1]
	Range	2.4 - 4.0	1.5 - 2.0
1972	Mean	3.9	
	Range	3.0 - 5.2	
1973	Mean	3.3	
	Range	2.3 - 4.3	
1977	Mean	3.3	2.7
	Range	2.3 - 4.3	1.8 - 3.8
1978	Mean	4.7	3.9
	Range	4.3 - 5.0	3.1 - 4.6
1979	Mean	3.4	3.8
	Range	1.2 - 4.9	3.2 - 4.6
1980	Mean	4.2	3.2
	Range	3.5 - 5.9	2.6 - 3.8
1981[2]	Mean	2.9	2.9
	Range	2.3 - 3.4	2.7 - 4.6

[1] Based on one sample in May and one in August.

[2] Secchi disc measurements were taken by a different observer who used a slightly different method that underestimated the readings.

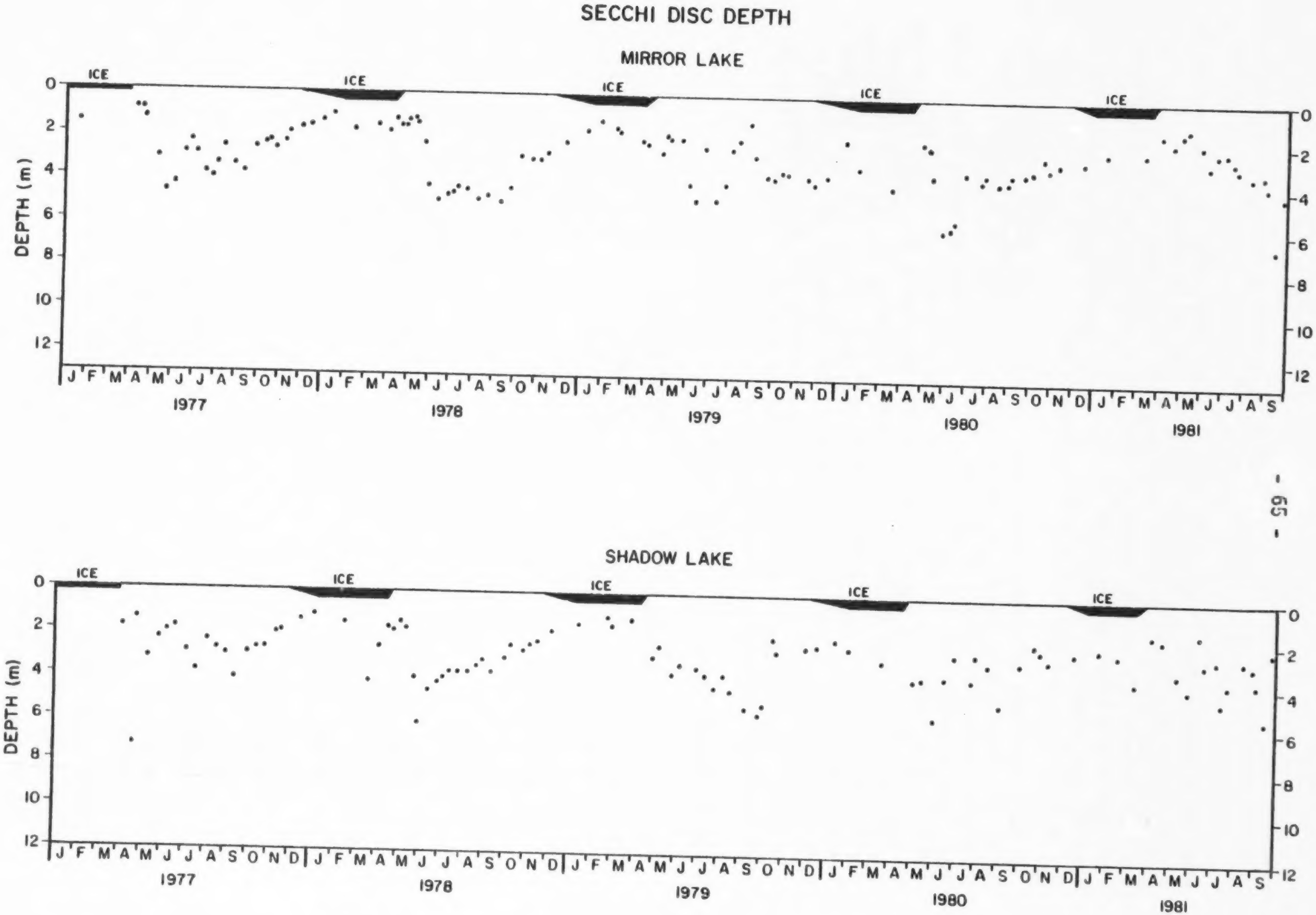


Figure 39. Secchi disc depths for Mirror and Shadow Lakes.

Chlorophyll a values were highest in the upper waters during spring, particularly before the alum treatment (Figures 40, 41). Concentrations exceeded 50 ug/l in Mirror Lake and 30 ug/l in Shadow Lake. The higher concentrations in Mirror Lake correspond to the higher phosphorus concentrations. The algal bloom was dominated in both lakes by the blue-green alga Oscillatoria agardhii var. (Figure 49a). Since this alga is able to survive under low light conditions, it is present in substantial quantities under the ice (Figure 50). With the melting of the ice, O. agardhii has an advantage over the other algae, such as diatoms, and continues to dominate the algal assemblage. This alga, which is red colored, often is trapped in the ice, giving the ice a reddish hue.

Since O. agardhii cannot survive in water temperatures above 20°C, it moves to deeper waters as stratification begins. In the lower metalimnion, this alga develops a highly concentrated layer (1 meter or less in thickness) where the peak chlorophyll a values may exceed 40 ug/l.

Since this alga characteristically incorporated most of the dissolved phosphorus in the lake during spring,the epilimnion became nutrient deficient as the population migrated to deeper water. Consequently, the chlorophyll concentrations in the epilimnion were low, ranging from 2-5 ug/l in the absence of large nutrient inputs. Chlorophyll values increased in the fall as the mixed zone reached the depth of the Oscillatoria layer. Consequently, the fall phytoplankton community was dominated by Oscillatoria (Figure 49a). This does not represent an increase in the Oscillatoria population, only a redistribution. Fee (1978) has also noticed an increase in the fall chlorophyll values because of a redistribution of a deep algal layer.

Following the alum treatment, the deep algal layer was reduced in Mirror Lake but maximum chlorophyll concentrations still exceeded 30 ug/l. This deep layer was strongly dominated by blue-green algae (Myxophyceae), primarily O. agardhii (Figure 42).

During the spring of 1979, chlorophyll a values were 10 ug/l, reduced from 50 ug/l the year before. In 1980, the values were further reduced to 5 ug/l and these were maintained in 1981. Spring values were also reduced in Shadow Lake in 1979 and 1980. In 1981, concentrations increased to 10 ug/l from 5 ug/l the previous year.

In 1979 the metalimnetic algal maximum was still present in Mirror Lake although somewhat reduced. In late June and more intensely in late August, the surface waters became turbid (as observed with the Secchi disc). This induced the O. agardhii to migrate upwards to obtain sufficient light to meet its photosynthetic requirements. In August, the Oscillatoria was forced into water where the temperature was greater than 20°C causing a decline in the population. This reduction can be seen in the reduced O. agardhii population in the fall phytoplankton community. In 1980, the deep layer was much reduced, but in 1981, the O. agardhii population returned in large concentrations in August and was dominant in the fall phytoplankton (Figure 49b).

The chlorophyll a concentrations in Shadow Lake were similar to those experienced in Mirror Lake, being low in the surface waters and increasing in the metalimnion. Unlike Mirror Lake, the deep chlorophyll layer did not decline in 1979, and has remained at similar levels since 1978. This deep layer was also dominated by O. agardhii.

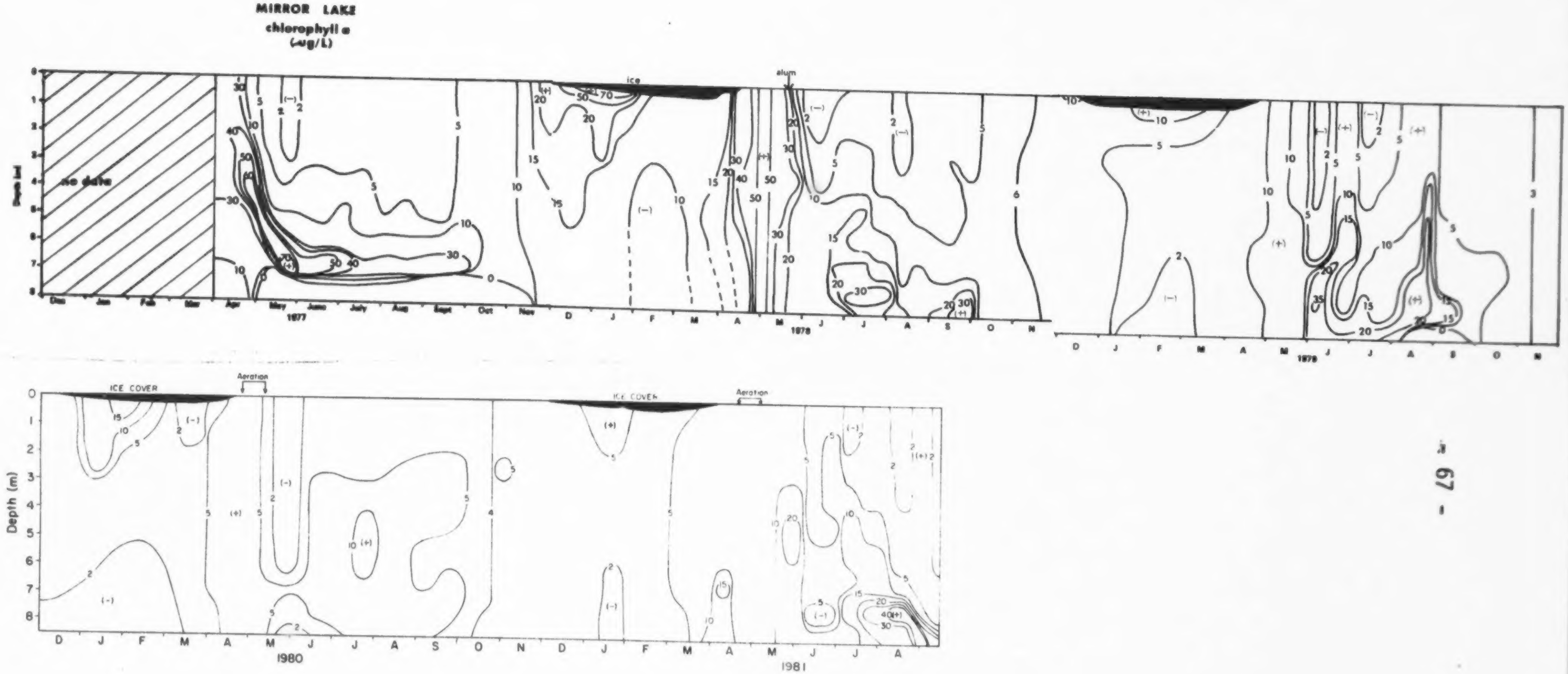


Figure 40. Chlorophyll a isopleths for Mirror Lake.

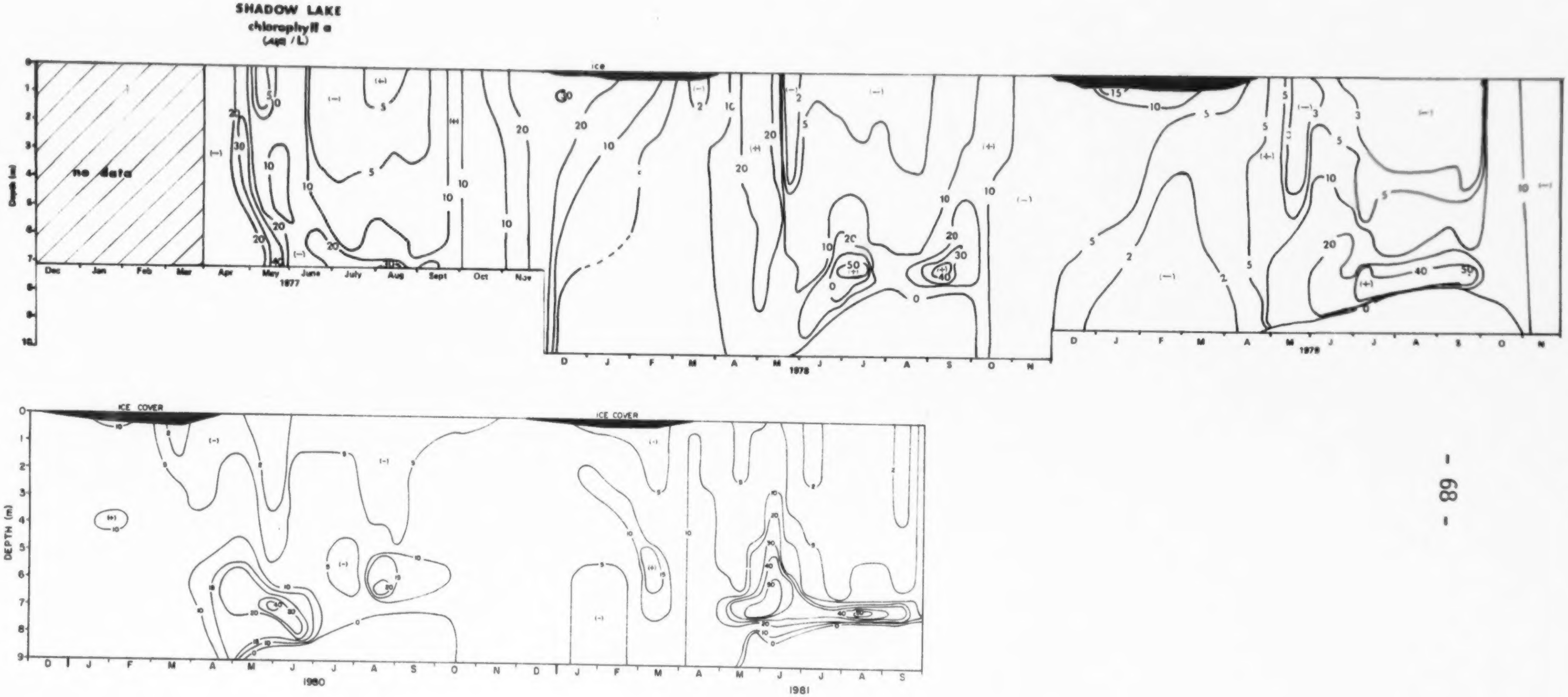


Figure 41. Chlorophyll a isopleths for Shadow Lake.

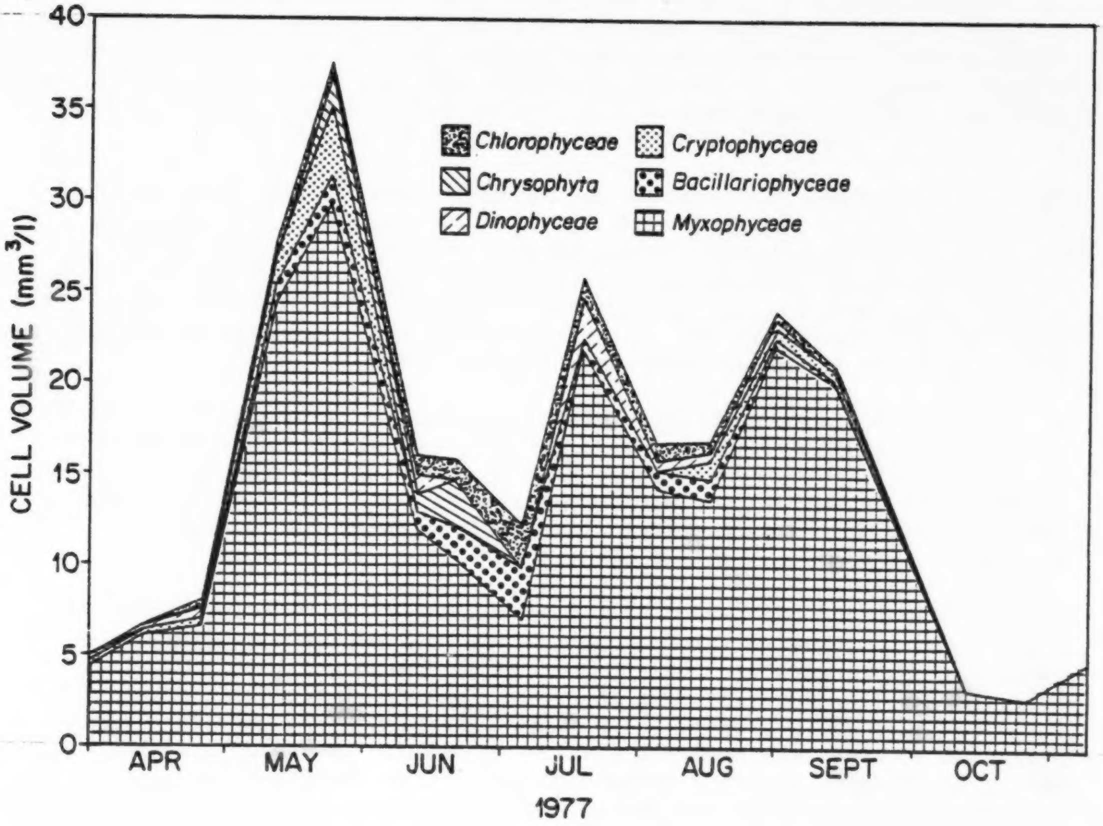


Figure 42. Phytoplankton biovolume at 6.5 in Mirror Lake in 1977.

Immediately below the layer of O. agardhii, the dissolved oxygen level dropped to zero and hydrogen sulfide was present. In this area, large communities of photosynthetic sulfur bacteria were present in both lakes. These bacteria require the presence of hydrogen sulfide and some light (albeit low intensities). Parkin and Brock (1980b) found that the light intensity was only 0.24 percent to 0.04 percent of surface intensities. Both purple and green sulfur bacteria are present with the dominant genera being Lamprocystis, Chromatium, Pelodictyon, and Chlorobium (Parkin and Brock, 1980a) in Mirror Lake. Both bacteriochlorophyll a and d are present in these lakes with bacteriochlorophyll d predominating. Figure 43 shows the seasonal trend of bacteriochlorophyll d in both lakes in 1978 and 1979. Maximum values of 100 ug/l and 163 ug/l were observed in Mirror and Shadow Lakes, respectively. Although photosynthetic bacteria can account for a large portion of the primary productivity (Culver and Brunskill 1969 and Cohen et al. 1977), Parkin and Brock (1980a) found that on one date in 1978, it only contributed to 3.8 percent of the total primary production in Mirror Lake.

Table 11 presents a taxa list of the pelagic phytoplankton found in Mirror Lake during the study period. The most numerous group were the Chlorophyta followed by the Chrysophyceae. Although not many species of Bacillariophyceae (diatoms) were encountered, there undoubtedly were many more species which were present as attached plankton in the littoral zone. The taxa list for diatoms in the sediment core included many more genera that were not encountered in the current study (Farris 1981).

In 1977 and 1978, the peak algal biovolume occurred in the spring in Mirror Lake. Following the alum treatment in 1978, the spring algal bloom was nonexistent with a brief biovolume peak occurring at the end of June (Figures 44-48). The peak biovolume was encountered in April and May, 1978, when the concentration exceeded 12 mm^3/l. The summer maximum usually was 3-4 mm^3/l, although in 1981 it was 6.5 mm^3/l.

The alum treatment appears to have been successful in reducing the spring algal bloom by reducing internal phosphorus loading. Spring biovolumes exceeded 8 mm^3/l in 1972, 1973 (Knauer 1975), 1977, and 1978, but since 1978, the peak spring biovolume concentrations have been approximately 3 mm^3/l. Summer biovolumes, while somewhat reduced from pre-storm sewer diversion levels, have remained similar throughout the study. Although there was no detectable inorganic phosphorus and little inorganic nitrogen in the epilimnion, the level of the phytoplankton community indicates that there must have been considerable recycling of these nutrients within the surface waters as observed with the sedimentation traps. Rigler (1964) has shown that phosphorus turnover time can be in a manner of minutes in the epilimnion. Nutrients can be recycled from excretion by phytoplankton, zooplankton, or bacterial mineralization of organic matter.

During the study, the Myxophyceae (blue-green) were usually the dominant phytoplankton during the spring and fall of 1977-1979 (Figure 49a). The dominant species was Oscillatoria agardhii Gom var. Since this was the main nuisance alga, it was hoped that storm sewer diversion and the alum treatment would eliminate this species. As discussed previously, the Oscillatoria

Table 11. Pelagic Phytoplankton Taxa List for Mirror Lake.

Division: Chlorophyta
Class: Chlorophyceae
Acanthosphaera zachariasi Lemmermann
Ankistrodesmus falcatus var. *mirabilis* (West & West) G.S. West
Botryococcus Braunii Kuetzing
Botryococcus sp.
Carteria Klebsii (Dang.) Dill
Cerasterias staurastroides West & West
Chlamydomonas angulosa Dill
C. Dinobryoni G.M. Smith
C. globosa Snow
Chlamydomonas spp.
Chlorella vulgaris Beyerinck
Closteriopsis longissima var. *tropica* West & West
Coelastrum reticulatum (Dang.) Senn
Cosmarium circulare Reinsch
C. depressum var. *achondrum* (Boldt) W. & G.S. West
Cosmarium sp.
Crucigenia apiculata (Lemm.) Schmidle
C. quadrata Morren
C. rectangularis (A. Braun) Gay
C. tetrapedia (Kirch.) West & West
C. truncata G.M. Smith
Crucigenia sp.
Elakatothrix gelatinosa Wille
Eudorina elegans Ehrenberg
Franceia Droescheri (Lemm.) G.M. Smith
Gloeocystis gigas (Kuetz.) Lagerheim
G. major Gerneck
G. planctonica (West & West) Lemmermann
Golenkinia paucispina West & West
G. radiata (Chod.) Wille
Lagerheimia citriformis var. *paucispina* Tiffany & Ahlstrom
L. quadriseta (Lemm.) G.M. Smith
L. subsalsa Lemmermann
Nephrocytium ecdysisceparum W. West
N. limneticum G.M. Smith
N. obseum West & West
Oocystis novae - semilae Wille
O. lacustris Chodat
O. parva West & West
O. pusilla Hansgirg
O. solitaria Wittrock
O. submarina Lagerheim
Oocystis sp.
Planktosphaeria gelatinosa G.M. Smith
Pediastrum obtusum Lucks
Quadrigula Chodatii (Tan.-Ful.) G.M. Smith
Scenedesmus abundans (Kirch) Chodat
S. arcuatus var. *capitatus* G.M. Smith

S. bijuga (Turp.) Lagerheim
S. obliquus (Turp.) Kuetzing
S. quadracauda (Turp.) de Brebisson
Scenedesmus sp.
Selenastrum minutum (Naeg.) Collins
Schroederia ancora G.M. Smith
S. Judayi G.M. Smith
S. setigera (Schrod) Lemmermann
Sphaerocystis Schroeteri Chodat
Spondylomorum quaternarium Ehrenberg
Staurastrum sp.
Tetraedron minimum (A. Braun) Hansgirg
T. regulare var. *granulata* Prescott
T. valdezi Kol
Tetraspora lamellosa Prescott
Treubaria setigerum (Archer) G.M. Smith
Westella sp.

Division: Cyanophyta
Class: Myxophyceae
Anabaena circinalis (Kuetz.) Rabenhorst
A. flos-aquae (Lyngb.) de Brebisson
A. planctonica Brunnthaler
A. Scheremetievi Elenkin
A. wisconsinense Prescott
Anabaena sp.
Aphanizomenon flos-aquae (L.) Ralfs
Aphanocapsa elachista West & West
A. pulchra (Kuetz.) Rabenhorst
Chroococcus dispersus var. *minor* G.M. Smith
C. limneticus Lemmermann
C. limneticus var. *carneus* (Chod.) Lemmermann
C. minimus (Keissl.) Lemmermann
Chroococcus sp.
Coelosphaerium kuetzingianum Naegeli
C. naegelianum Unger
Gloeothece rupestris Bornet
Merismopedia glauca (Ehr.) Naegeli
M. punctata Meyen
M. trolleri Bachmann
Microcystis incerta Lemmermann
Lyngbya spirulinoides Gomont
Oscillatoria agardhii Gomont
O. agardhii Gomont var.
O. geminata Meneghini
O. limosa (Roth) C.A. Agardh
O. tenuis C.A. Agradh
Rhabdoderma Gorskii Woloszynska

- Division: Chrysophyta
  - Class: Bacillariophyceae
    - *Achnanthes minitissima* Kutzing
    - *Achnanthes* sp.
    - *Asterionella formosa* Hassal
    - *Cocconeis placentula* Ehrenberg
    - *Coscinodiscus* sp.
    - *Cyclotella bodanica* Eulenstein
    - *C. comensis* Grunow
    - *C. comta* (Ehr.) Kutzing
    - *C. glomerata* Bachman
    - *C. Kuetzingiana* Thwaites
    - *C. Meneghiniana* Kutzing
    - *C. michiganiana* Skvortzow
    - *Cyclotella* spp.
    - *Cymbella cymbiformis* Agardh
    - *C. minuta* Hilse *ex* Rabenhorst
    - *C. minuta* var. *silesiaca* (Bleisch *ex* Rabh.) Reim.
    - *Cymbella* sp.
    - *Diatoma hiemale* (Roth) Heiberg
    - *D. tenue* var. *elongatum* Lyngbye
    - *D. vulgare* Bory
    - *Fragilaria capucina* Desm.
    - *F. construens* (Ehr.) Grun.
    - *F. crotonensis* Kitton
    - *F. pinnata* Ehrenberg
    - *Gomphonema truncatum* var. *capitatum* (Ehr.) Patrick
    - *Gomphonema* sp.
    - *Melosira ambigua* (Grun.) Muller
    - *M. granulata* (Ehr.) Ralfs
    - *Melosira* sp.
    - *Navicula zanoni* Hust.
    - *Navicula* sp.
    - *Nitzschia acicularis* W. Smith
    - *N. palea* (Kutz) W. Smith
    - *Nitzschia* sp.
    - *Rhizosolenia erensis* H.L. Smith
    - *Stephanodiscus astrea* (Ehr.) Grunow
    - *S. niagarae* Ehrenberg
    - *S. tenuis* Ehrenberg
    - *Synedra acus* Kutzing
    - *S. delicatissima* W. Smith
    - *S. delicatissima* var. *augustissima* Grunow
    - *S. radians* Kutzing
    - *S. ulna* (Nitz.) Ehrenberg

  - Class: Chrysophyceae
    - *Chromulina pygmaea* Nygaard
    - *Chrysapsis* sp.
    - *Chrysocapsa planctonica* (West & West) Pascher
    - *Chrysochromulina parva* Lackey
    - *Chrysococcus* sp.
    - *Dinobryon bavaricum* Imhof
    - *D. cylindricum* Imhof

- *D. sociale* var. *americanum* (Brunn.) Bachmann
- *Dinobryon* sp.
- *Erkenia subaequicilata* Skuja
- *Hylobryon mucicola* (Lemm.) Pascher
- *Kephryion impletum* Nygaard
- *Kephryion* sp.

Division: Chrysophyta
  Class: Chrysophyceae
- *Mallomonas acaroides* Perty
- *M. acaroides* var. *moskovensis* (Wermel) Krieger
- *M. akrokomos* Ruttner
- *M. caudata* Iwanoff
- *M. fastigata* var. *macrolepsis* Conrad
- *M. producta* (Zacharias) Iwanoff
- *M. producta* var. *marchica* Lemmermann
- *M. pseudocoronata* Prescott
- *Mallomonas* spp.
- *Ochromonas* sp.
- *Synura uvella* Ehrenberg

Class: Xanthophyceae
- *Planctonema Lauterborni* Schmidle

Division: Pyrrhophyta
  Class: Cryptophyceae
- *Chroomonas acuta* Utermohl
- *C. coerulea* (Geitl.) Skuja
- *C. reflexa* Kisselew
- *Chroomonas* spp.
- *C. obovata* Skuja
- *Cryptomonas* spp.
- *Cyanomonas coerulus* Lackey

Class: Dinophyceae
- *Ceratium hirundinella* (O.F. Muell.) Dujardin
- *Glenodinium palustre* (Lemm.) Schiller
- *G. pulvisculus* (Ehrenb.) Stein
- *Glenodinium* sp.
- *Gymnodinium palustre* Schilling
- *Gymnodinium* sp.
- *Peridinium cinctum* (Muell.) Ehrenberg
- *P. cinctum* var. *tuberosum* (Meunier) Lindermann

Division: Euglenophyta
  Class: Euglenophyceae
- *Phacus pyrum* (Ehrenb.) Stein
- *Trachelomonas robusta* Swirenko
- *Trachelomonas* sp.

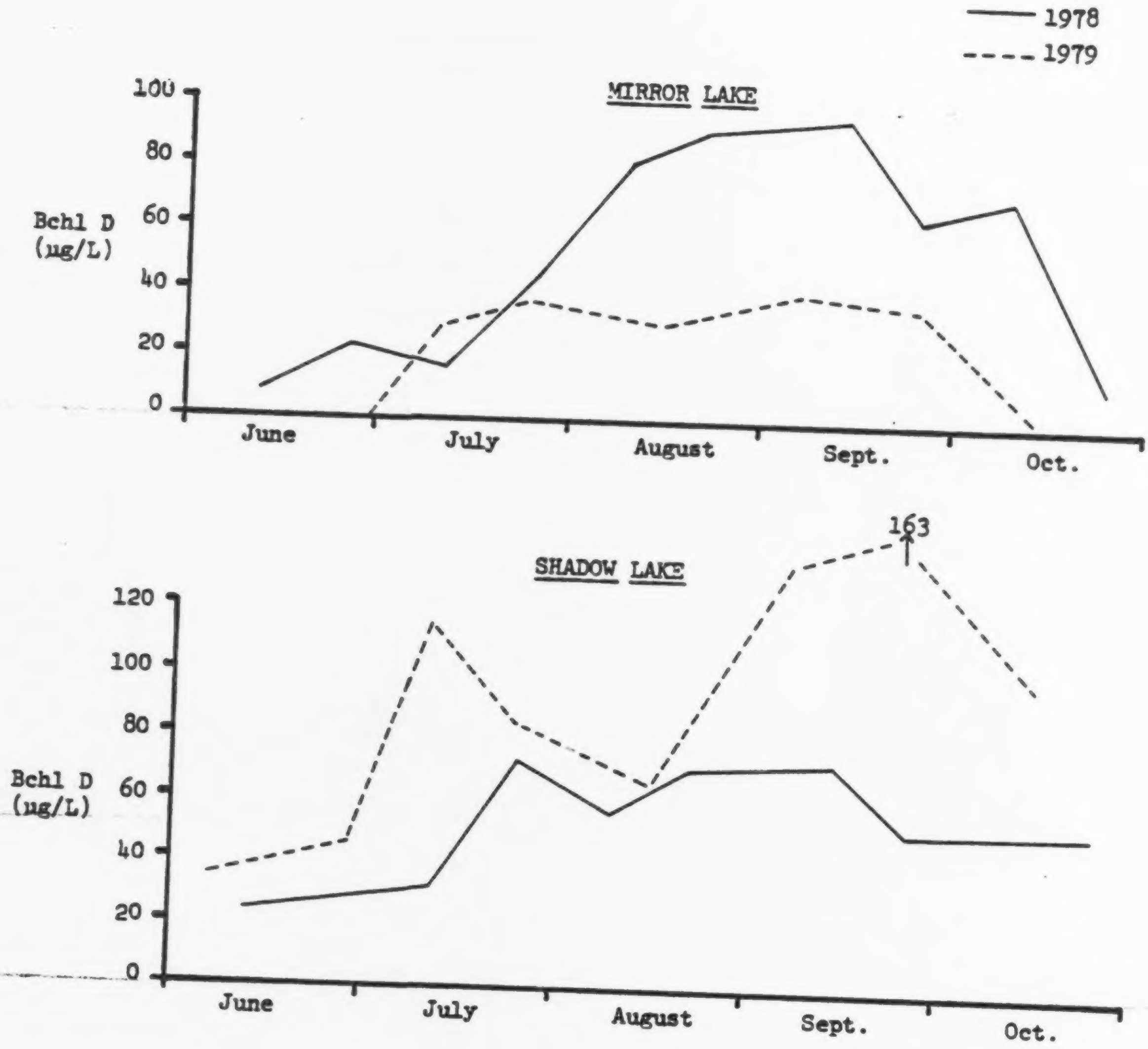


Figure 43. Bacteriochlorophyll d for Mirror and Shadow Lakes.

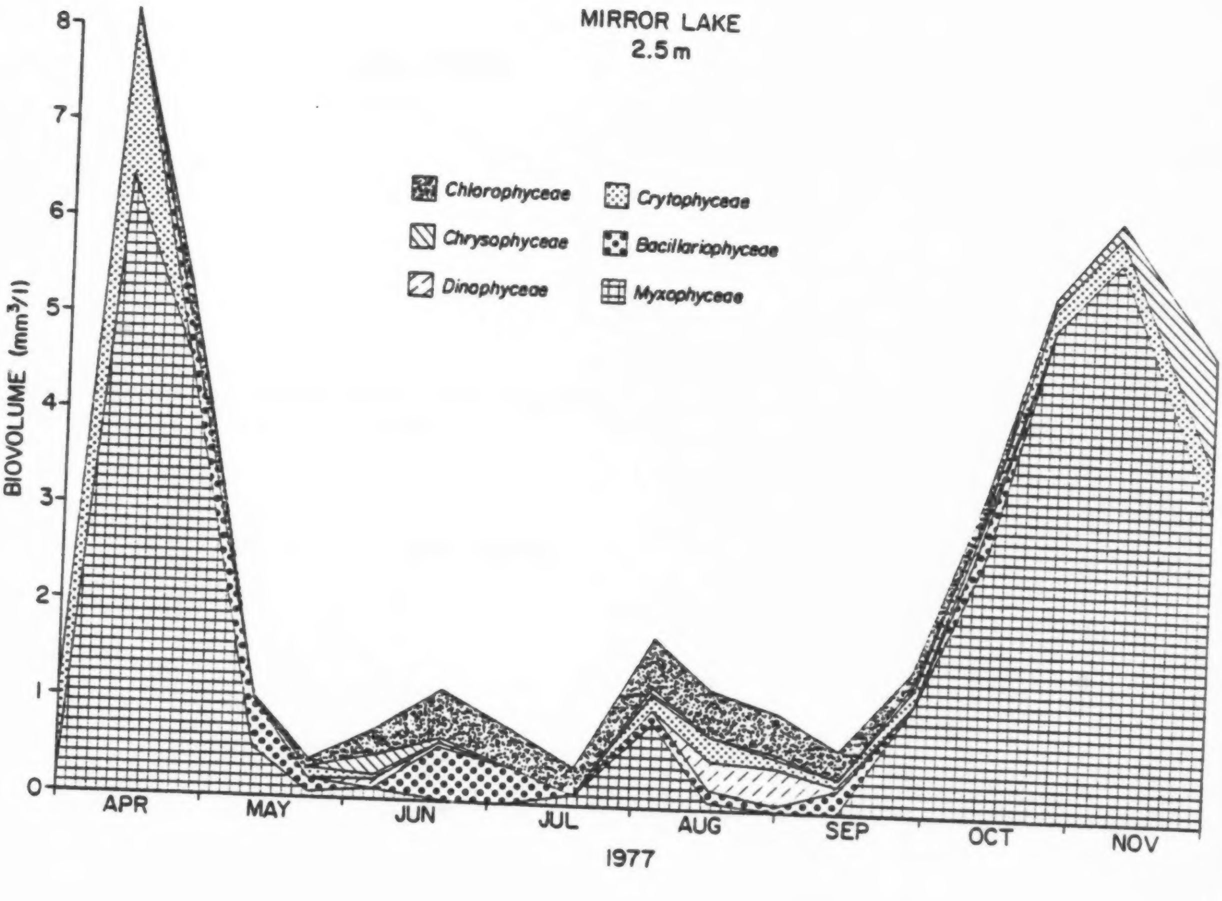


Figure 44. 1977 algal biovolume in Mirror Lake.

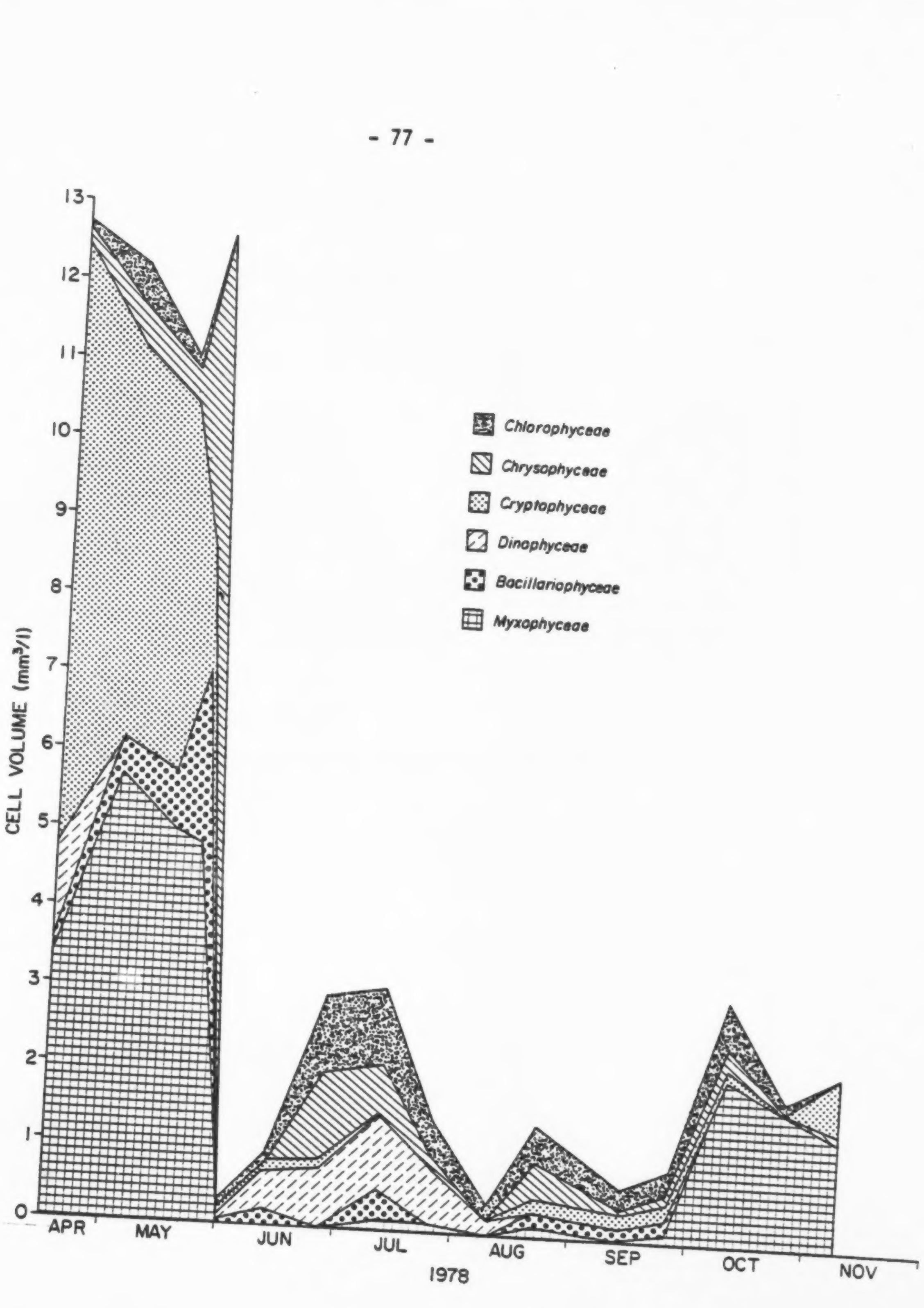


Figure 45. 1978 algal biovolume in Mirror Lake.

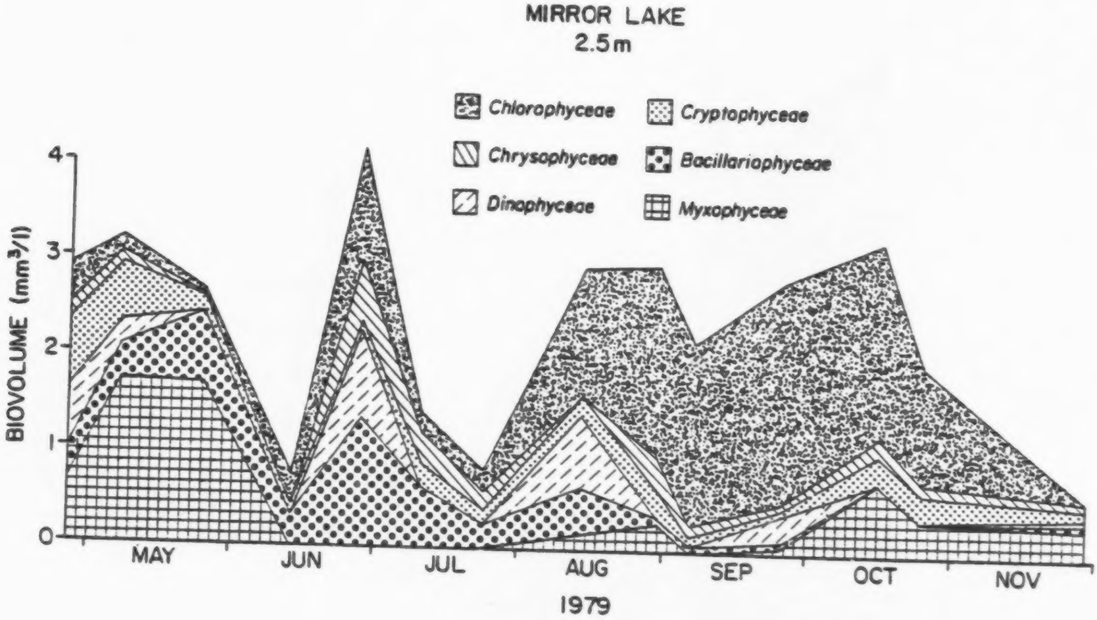


Figure 46. 1979 algal biovolume in Mirror Lake.

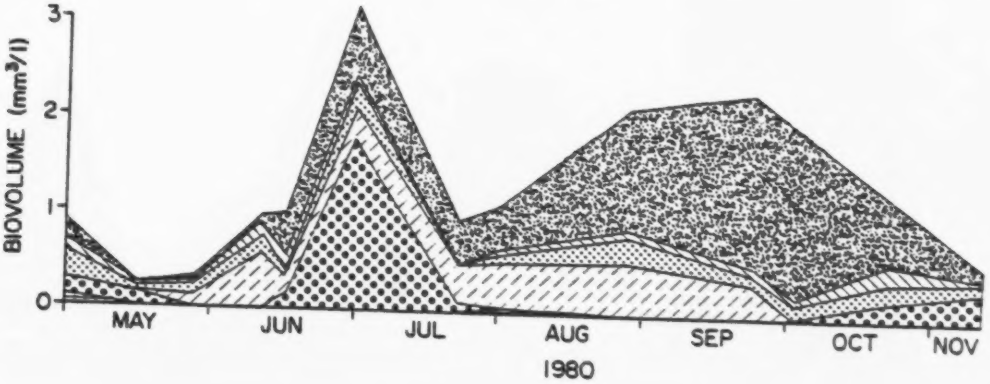


Figure 47. 1980 algal biovolume in Mirror Lake.

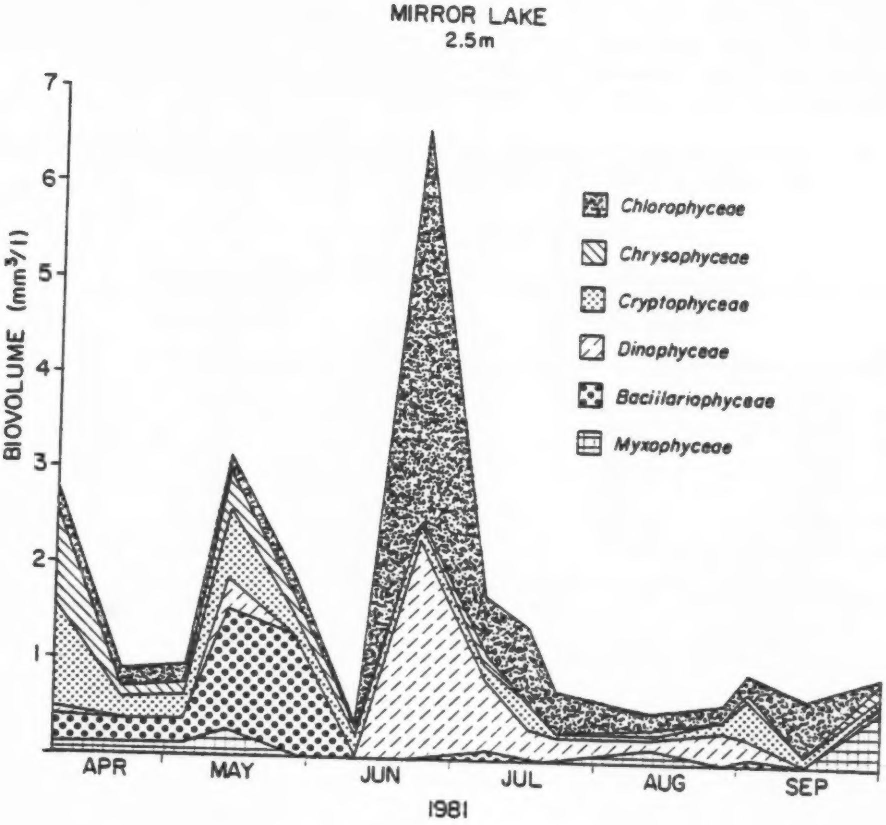


Figure 48. 1981 algal biovolume in Mirror Lake.

population was virtually eliminated in Mirror Lake in 1980, but returned in 1981. In Shadow Lake, the population remained at a relatively constant density. Because of the narrow band and highly concentrated nature of this alga during stratification, it was difficult to estimate the population size. This could best be done in the fall when the population was suspended throughout the whole water column, or at least the upper waters. Table 12 compares the fall population of *Oscillatoria* in Mirror and Shadow Lakes. Since the lakes were not always *completely* mixed when the samples were taken, the total biovolume in the lake was computed. The *Oscillatoria* population in both lakes declined from 1977 through 1980, especially in Mirror Lake. The population in 1981 appeared to reach levels comparable to 1979. Although the population declined somewhat in Shadow Lake, it still constituted 70-80 percent of the total fall biovolume.

Table 12. Equalized *Oscillatoria agardhii* var. population size and percentage of total community biovolume.

Mirror Lake

Date	*Oscillatoria* Biovolume (mm^3/l)	Total Mass (g x 10^6)	Population Percentage %
28 Nov. 1972	11.95	4.9	90+
28 Nov. 1977	3.24	1.3	66
7 Nov. 1978	1.39	0.5	60
28 Nov. 1979	0.30	0.1	43
11 Nov. 1980	0.006	0.002	1
1 Oct. 1981	0.60	0.2	57

Shadow Lake

Date	*Oscillatoria* Biovolume (mm^3/l)	Total Mass (g x 10^6)	Population Percentage %
28 Nov. 1972	4.05	3.7	80
28 Nov. 1977	5.70	4.5	91
7 Nov. 1978	3.60	3.3	83
28 Nov. 1979	2.87	2.6	79
11 Nov. 1980	0.76	0.7	73

In the spring of 1978, Cryptophyceae made up a sizable part of the phytoplankton community in Mirror Lake. This probably was the result of the low oxygen concentrations found under the ice the previous winter (Figure 9). Schindler and Comita (1972) observed that cryptomonads dominated the winterkill lake they studied.

During the summer, the algal community was a mixture of Chlorophyceae, Dinophyceae, and occasionally Bacillariophyceae and Cryptophyceae. The Chlorophyceae (green algae) were represented by colonial forms such as Sphaerocystis Schroeteri, Planktosphaeria gelatinosa, Coelastrum reticulatum, and several species of Oocystis (Figure 49a, b). Bacillariophyceae (diatoms) were usually only present in late June and represented by Cyclotella comensis and C. comta. The summer algal peak in late June usually followed the seasonal zooplankton peak (Figure 52). The dominant epilimnetic phytoplankton were gelatinous green algae and diatoms. Porter (1972, 1975) has found that gelatinous algae can be enhanced by zooplankton gut passage.

Figure 49a, b shows the seasonal trend of some of the dominant phytoplankton. Noticeably absent during summer stagnation are blue-green algae such as Anabaena and Chroococcus which were an important part of the plankton in 1972 and 1973 (Knauer 1975). With the absence of storm sewer input, nutrients were not present in sufficient concentrations to support a substantial blue-green community.

The winter phytoplankton community also portrays the lake improvement following the storm sewer diversion and alum treatment (Figure 48). In 1977-78, Myxophyceae, dominated by O. agardhii made up the majority of the population. This population provided a good seed base for the late spring bloom in 1978. In the winters 1979-80 and 1980-81, phytoplankton biovolume was greatly reduced with almost no O. agardhii present. In early winter, 1979-80, the diatom Asterionella formosa dominated, but was replaced by cryptomonads. The winter biovolumes of following years were similar but no one group dominated.

Depth profiles of primary production were often similar to those observed in other mesotrophic lakes (Wetzel 1975, and Rott 1981). Four different types of profiles were observed. These were characterized by maxima in the following

- surface layer or immediately under the ice cover,
- subsurface layer (1.5 and 2.5 m),
- middle portion of the thermocline (4.5 m),
- lower part of the euphotic zone (8.5 m).

There were also transitional types with one maxima being in the subsurface layer and another in the thermocline region. Maximum values of primary production per hour were usually less that 30 mgC/m^3, but during the spring bloom in 1978, peak values were 105 mgC/m^3/hr.

Minimum production rates were during ice-cover and late fall (0.05-0.21 gC/m^2/day)(Figure 51). Productivity rates during the ice free period followed the seasonal trends in phytoplankton biovolume. The highest observed productivity was in early May 1978 when the biovolume was also high. With a reduction in spring biovolume in the succeeding years, the productivity also decreased. Summer productivity rates were often higher in early summer, decreasing in August through the fall.

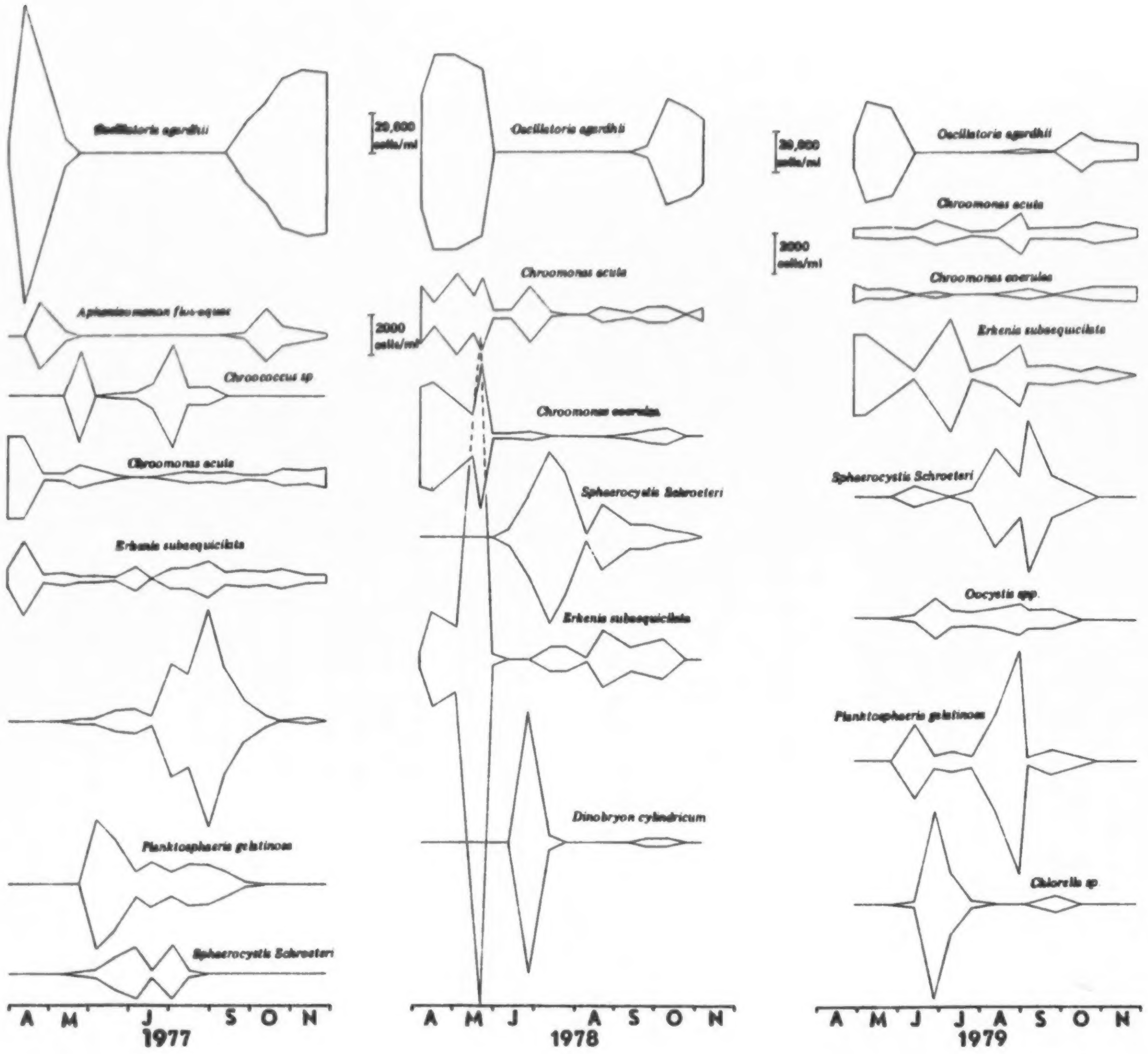


Figure 49a. Seasonal succession of phytoplankton in Mirror Lake.

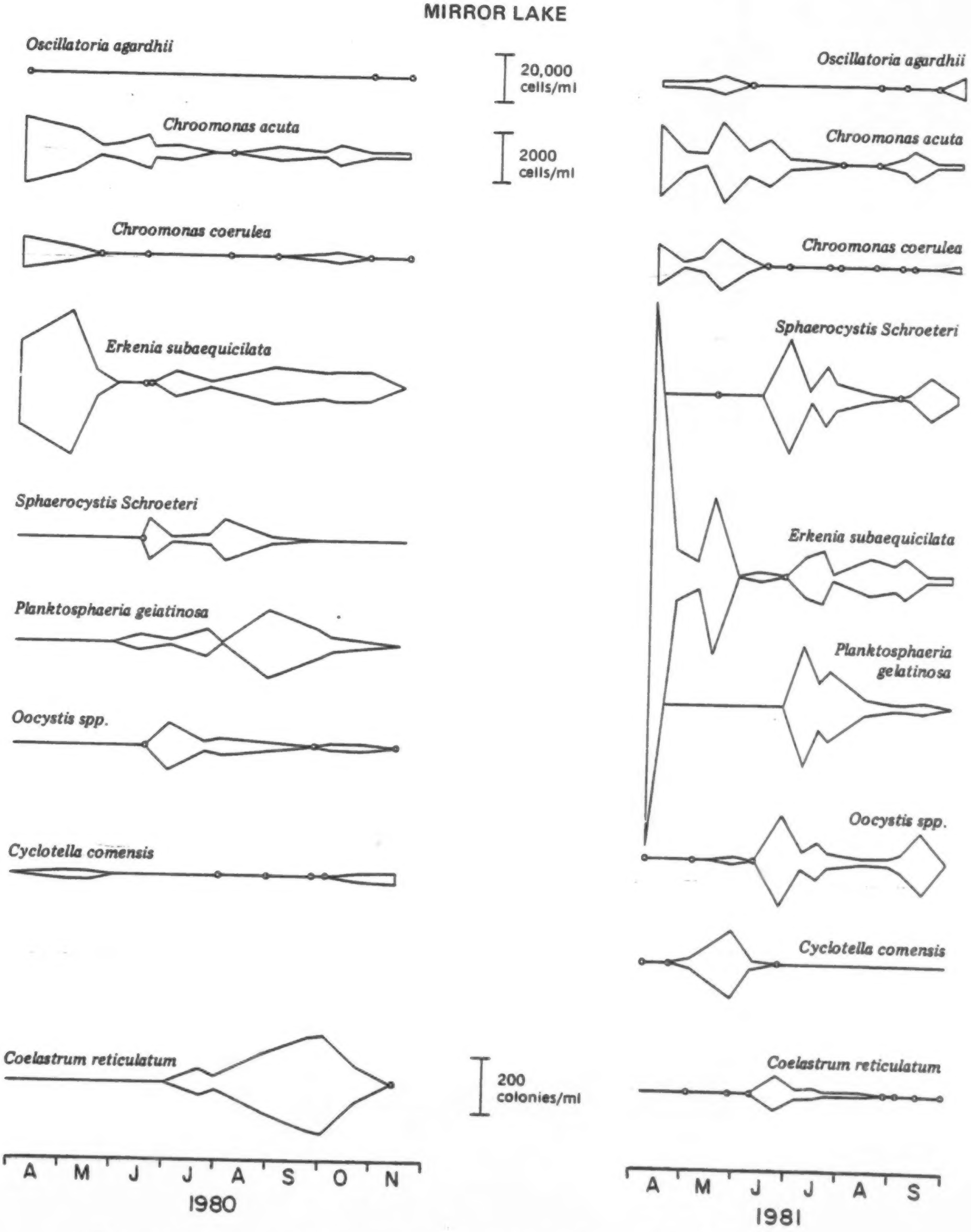


Figure 49 b. Seasonal succession of phytoplankton in Mirror Lake.

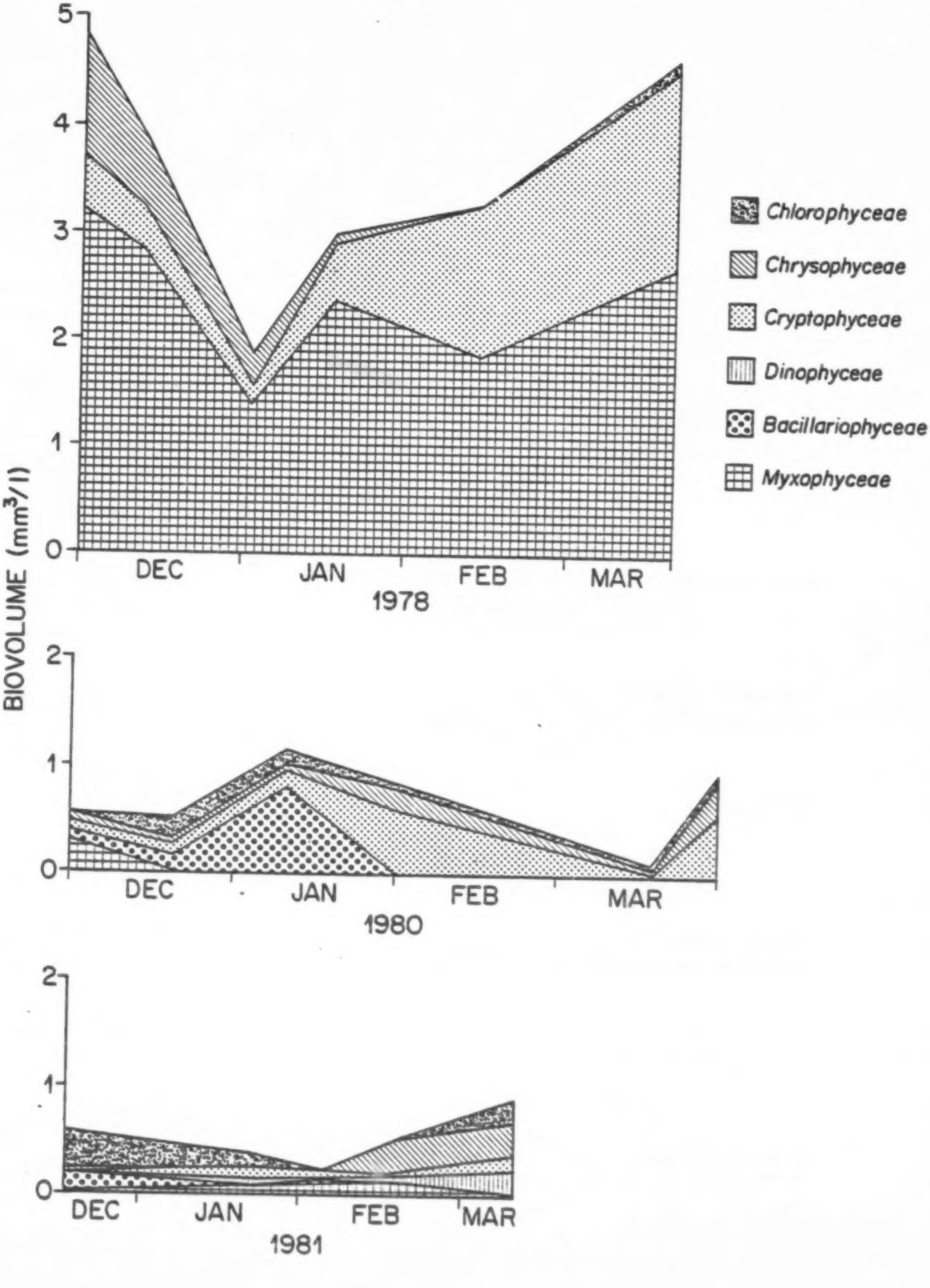


Figure 50. Winter phytoplankton in Mirror Lake.

Annual primary production for the years 1978-1980 was highest in 1978 (233 gC/m^2/yr.) (Table 13). The main reason for the increased production was the high productivity rates during spring mixing. In 1977 and 1972 when large phytoplankton populations were present in the spring, the annual production was higher than the other years (1979-1981). Following the alum treatment with the reduction of the spring bloom, the summer production contributed to a larger portion of the annual production. Summer production was less in 1979, the first full year following the alum treatment, and the two succeeding years.

Table 13. Annual and summer primary production for Mirror Lake.

	June - Sept gC/m^2	Annual gC/m^2/yr	Proportion of Summer to Annual
1977	112	(214)[a]	52%
1978	129	233	55%
1979	92	147	63%
1980	78	123	63%
1981	86	(131)[a]	66%
1972	103	(190)[a,b]	54%

[a] Production during months not measured was estimated.
[b] From Knauer (1975).

The Rotifera were the most numerous zooplankton found in Mirror Lake followed by Copepoda and Cladocera (Figure 52). Since the Rotifera are smaller in size than the other two classes, they may not have dominated on a biomass basis. There were 13 species of rotifers found during the study in the pelagic zone (Table 14). The dominant rotifer was Keratella cochlaris although other species were important at times. The main cyclopoid copepod was Cyclops bicuspidatus thomasii while Diaptomus oregonensis, and D. pallidus were the two equally important calanoid copepods. There were 7 species of Daphnia found during the study which is a large number for one lake although D. galeata mendotae and D. retrocurva were the dominant.

The seasonal peak of all three zooplankton groups occurred during mid to late spring in response to the spring algal bloom. In response to the decrease in the spring algal community following the alum treatment, seasonal zooplankton peaks were also reduced. The reduction in the zooplankton community level did not appear to be a response to aluminum toxicity from the alum treatment as sizeable populations were maintained during the summer.

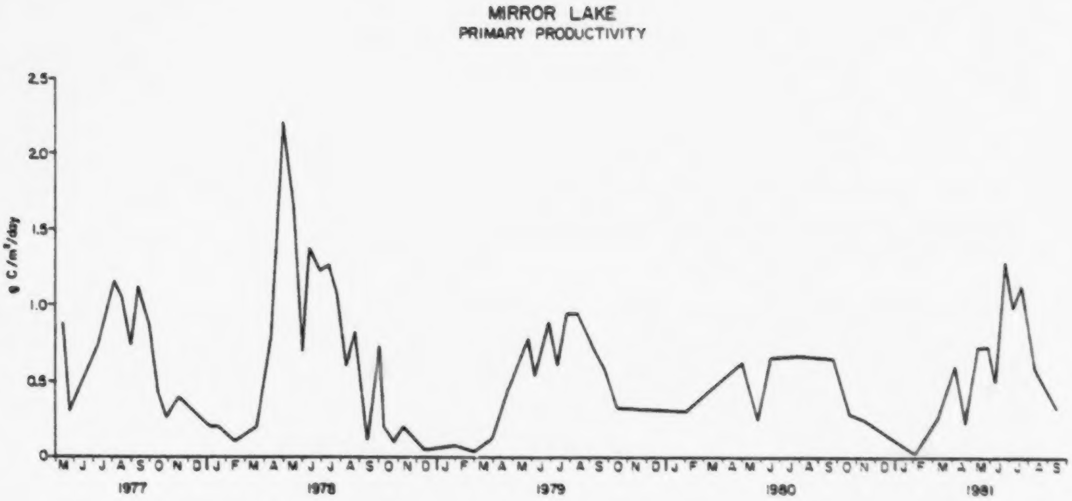


Figure 51. Primary productivity for Mirror Lake.

Table 14. Pelagic zooplankton taxa list for Mirror Lake.

Rotifera

Asplanchna sp.
Chromogaster sp.
Conochilus unicornis Rousselet
Filinia terminalis Plate
Kellicottia bostoniensis Rousselet
K. longispina Kellicott
Keratella cochlearis Gosse
K. quadrata Muller
Monostyla lunaris Ehrenberg
Notholcea sp.
Polyarthra euryptera Wierzejski
P. vulgaris Carlin
Trichocerca sp.

Cladocera

Bosmina longirostris O.F. Muller
Ceriodaphnia lacustris Birge
Daphnia ambigua Scourfield
D. galeata mendotae Birge
D. laevis Birge
D. longiremus Sars
D. parvula Fordyce
D. pulicaria S.A. Forbes
D. retrocurva S.A. Forbes
Diaphanosoma leuchtenbergianum Fischer
Eubosmina coregoni Baird
Leptodora kindtii Focke

Copepoda
Calanoida

Epishura lacustris S.A. Forbes
Skistodiaptomus oregonensis Lilljeborg
S. pallidus Herrick

Cyclopoida

Cyclops bicuspidatus thomasi S.A. Forbes
Ergasilus sp.
Mesocyclops edax S.A. Forbes
Orthocyclops modestus Herrick
Tropocyclops prasinus Fischer

Diptera

Chaoborus punctipennis Say
Chironomus sp.

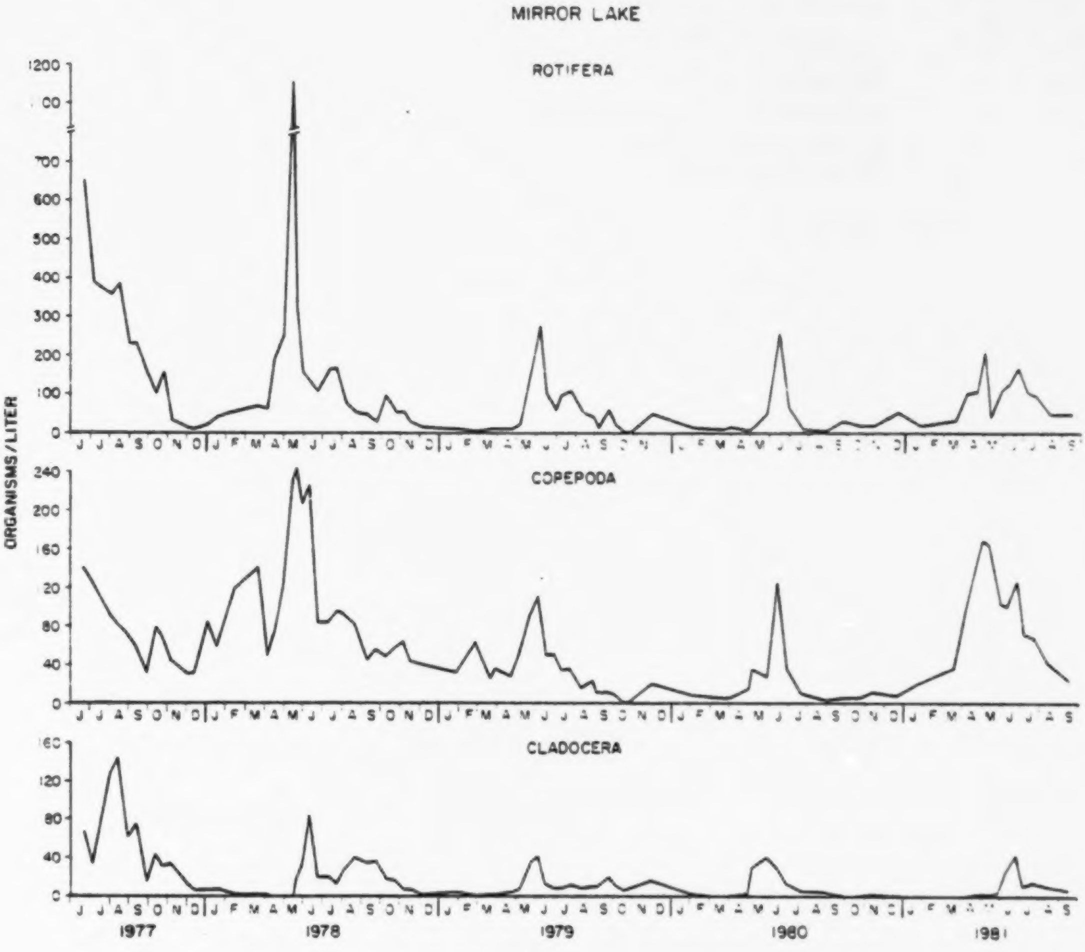


Figure 52. Mirror zooplankton seasonal trends.

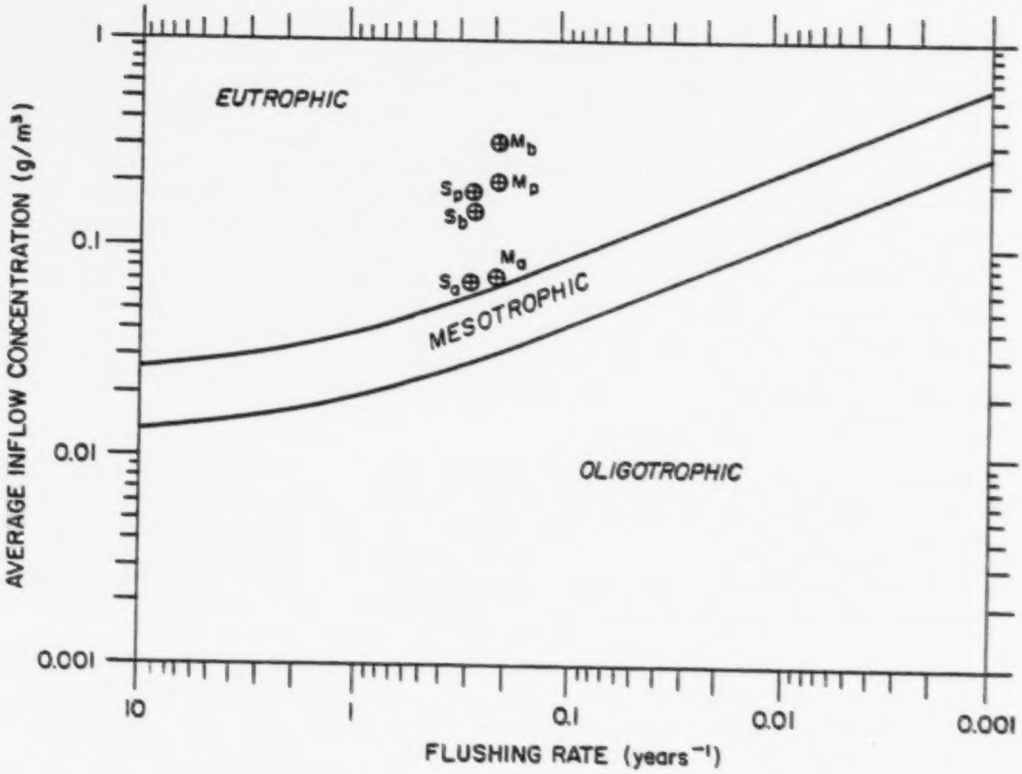
DISCUSSION

With a multi-faceted restoration project such as this, the obvious question arises as to whether one or two restorative procedures could have been eliminated. For example, what if only the storm sewers were diverted? What if a series of alum treatments were completed without diverting the storm water runoff? Or what if only destratification were employed?

The fall destratification of Mirror Lake was probably the single most important restoration step in preventing winter fish kill. While the storm sewer diversion and alum treatment undoubtedly resulted in a lessening in the algal community size, and therefore decreasing the liklihood of winter kills, other factors inherent in Mirror Lake would still make it susceptible to fish kills. Its small surface area combined with its depth and location in a depression make it unlikely that enough wind power would be present to completely mix the lake in the fall. Also, because of past watershed activities, the lake bottom waters become anaerobic with resultant increase in strong reducing substances (e.g. hydrogen sulfide) thus creating a high chemical oxygen demand. When the lake does mix, the high oxygen demand causes a sharp decrease in the oxygen level throughout the water column as evidenced in 1977 (Figure 9). It is to be expected that because of the nature of the sediments in Mirror Lake, large amounts of reducing substances will continue to be present.

It probably is not imperative that Mirror Lake be artificially mixed in the spring. Shadow Lake did not always mix in the spring and this did not seem to adversely affect the ecology of the lake. One detrimental side effect of spring mixing is the increase in the temperature in the bottom waters. Holdren and Armstrong (1980) have demonstrated that more phosphorus can be released from the sediments as water temperatures are increased.

Diversion of a major nutrient source, (e.g. storm sewers) has been shown to improve lake water quality (Edmondson 1977, Ahlgren 1972, and Fuhs et al. 1977). There are other cases where improvement has not been immediate (Welch 1977). Shagawa Lake is an example where the major nutrient source was diverted, however because of internal loading, recovery of the lake water quality was limited (Larsen et al. 1981). On the basis of empirically developed phosphorus loading, (e.g. Vollenweider 1976) it is possible to predict or describe the change in trophic condition following restoration of many lakes (Uttormark and Hutchins 1980). Using a Vollenweider input-output type approach can only be viewed as describing the potential condition of the lake as it does not take into account the significance of internal loading or biological interactions. Mirror Lake was actually more eutrophic before storm sewer diversion than predicted because of internal phosphorus loading (Figure 53). Shadow Lake was closer to the predicted level indicating that internal loading was not as important. Largely because of internal loading, the lakes did not respond as might be expected by a Vollenweider type model. One year after storm sewer diversion, the predicted phosphorus concentration in Mirror Lake was 40 ug/l using the phosphorus residence time model of Sonzogni et al. (1976), and the loading model of Vollenweider (1976). The actual concentration at spring turnover was 92 ug/l, very similar to prediversion spring concentrations. Shadow Lake responded in much the same way with the spring phosphorus concentration being 46 ug/l one year after diversion, the same concentration as the previous spring. It appears, as with Shagawa Lake, internal phosphorus loading was modifying the anticipated recovery time of these lakes.



M = Mirror Lake

S = Shadow Lake

b - post diversion
p - pre-diversion
a - post alum treatment

Figure 53. Potential trophic status from phosphorus loading rates for Mirror and Shadow Lakes.

To facilitate a more rapid improvement in water quality, it was necessary to reduce the internal phosphorus loading. The deep water application of aluminum sulfate was the lake management technique used. As noted in Figure 53, the lake's tropic condition should have been reduced following the storm sewer diversion to a slightly eutrophic condition with a phosphorus concentration of 22 ug/l. This was not achieved until after the alum treatment. The resultant lake conditions after treatment were almost exactly what was predicted by Vollenweider's (1976) model. The alum treatment in conjunction with the storm sewer diversion greatly reduced the phosphorus concentrations in both lakes.

Because an alum treatment resulted in such a marked reduction in the phosphorus level, it might appear beneficial to not divert the storm sewers; however, three cases illustrate the necessity for diverting the nutrient source. The first lake treated with alum was Lake Langsjon in Sweden. Jernelov (1970) observed that while the treatment greatly reduced the lake phosphorus concentration, heavy runoff the following spring returned the phosphorus concentration nearly to pretreatment levels. The first lake treated in Wisconsin, Horseshoe Lake, received phosphorus loading from agricultural runoff. While the input was not reduced before the alum treatment, the application greatly reduced the inlake phosphorus concentration. Born (1979) reported that the hypolimnetic phosphorus concentration steadily increased each succeeding year following the treatment. It appears that phosphorus is not diffusing from the sediments through the alum layer but instead, particulate phosphorus sedimenting on top of the alum layer is remineralized and diffusing into the water column. Liberty Lake in the state of Washington was treated with alum in 1974. Because the major external nutrient sources were not diverted, results of the treatment were shortlived, causing Funk et al. (1980) to conclude that the longevity of an alum treatment was only two to three years.

What would be the expected results in the few years following the alum treatment? It is apparent from the above examples that external phosphorus loadings must first be reduced to an acceptable level before alum can successfully be used as a lake management technique. Without a reduction in the phosphorus loading via storm water diversion, the inlake phosphorus concentrations in Mirror and Shadow Lakes would have been reduced to about 20 ug/l with a reduction in the associated spring algal blooms. Before the storm sewer diversion or alum treatment, the summer epilimnetic phosphorus concentrations and associated algal concentrations were relatively low as the result of the spring Oscillatoria bloom scavenging P and N from the water column and migrating to deeper waters. Knauer (1975) noted, however, following heavy rains the resultant phosphorus influx from the storm sewers caused an increase in productivity and a shift in algal composition to Anabaena. It was further noted (Peterson and Knauer, unpublished report) that an increase in phosphorus concentration of 8 ug/l in late summer 1972 resulted in the algal community increasing 5.5 mm^3/l. Vollenweider (1968) noted that theoretically algal biomass may increase 1 mm^3/l for 1 ug/l increase in available phosphorus. An alum treatment without storm sewer diversion would not prevent these summer blooms.

The actual and conjectured response of Mirror and Shadow Lakes is analogous to two lakes described by Findenegg (1964). Both the 19 Km^2 Worthersee and the smaller (1 Km^2) Klopeiner See contain populations of Oscillatoria. Findenegg noted that when both lakes stratify the higher concentrations of nutrients in the hypolimnion are effectively cut off from the phytoplankton community in the epilimnion. This community must, therefore, derive its nutrients from recycling and external nutrient sources. In Worthersee, the algal biovolume steadily declined during the summer from the spring maximum because nutrients lost from sedimenting particles are not sufficiently replaced by external loading. This is exactly the temporal trend exhibited in Mirror Lake in 1977 and 1978. The algal biovolume steadily increased in Klopeiner See from a low in spring to a maximum in August because the greater loading rate from external sources more than replaced the phosphorus lost by sedimenting algae. This is the trend seen in the algal community in Mirror Lake in 1972 and what would be expected if an alum treatment were performed without storm sewer diversion.

In conjunction with this limnological evaluation of the Mirror and Shadow Lakes project, a socio-economic evaluation was also conducted (Bouwes and Klessig 1981). This project was a locally initiated one with property owners on Mirror Lake requesting assistance in 1968-1969 to deal with algal blooms and winter kills. While the problem was studied and acted upon from 1971-1973, it met little success in clearing up the lake's problems. When Federal monies became available, a grant was obtained in 1976. Since the project was first initiated by local citizenery, it has had good local support. Because the project implementation was handled directly by the Waupaca City Council, there was minimal citizen participation. Only 2 percent of Waupaca residents attended an annual lake district meeting (Bouwes et al. 1980). In contrast at rural White Clay Lake where a similar project occurred but with more citizen participation, half the residents attended annual meetings. Since the project caused no displacement of the labor force, changes in residential patterns, or diminution of services, the social impacts were judged to be neutral or positive (Bouwes and Klessig 1981).

Fishing pressure seems to have increased in both lakes, especially Shadow Lake, since initiation of the restoration project. Records of a local bait shop indicate that the quality and size of fish caught in these lakes has increased substantially since 1976. While this does not necessarily mean that the fishing is better, it does indicate that people are either more successful while fishing or they are fishing more often because they expect to be more successful. A public fishing dock was put in after the restoration project and is used heavily.

Local revenues for the project were raised by levying a two-year 0.9 mill rate tax on all real property in the city. This resulted in approximately $90 for a $50,000 home. The taxing rate was not weighted, so that people living near the lake paid the same amount as residents living farther away.

Bouwes et al. (1980) determined that the benefit-cost ratio ranged from 1.776 to 2.385. They calculated the discounted project costs as being from $439,872 to $469,650. The discounted project benefits were $833,958 to $1,049,269.

The homes surrounding Mirror Lake are generally larger, older houses whose values were depressed prior to the project. Because of the number of lakes in the immediate vicinity and high energy costs, the restoration work did not protect their value. On the other hand, local real estate firms and the city assessor felt that the project protected the property values around Shadow Lake. This occurred even though Mirror Lake's water quality was more strongly impacted by the storm sewer diversion.

It is expected that the lake restoration work performed on Mirror and Shadow Lakes will maintain these lakes in their present condition for many years to come. Since both these lakes are essentially seepage lakes in an urban residential setting, loading rates from their watersheds should remain constant. With no increase in external phosphorus loading, Vollenweider's (1976) model predicts that these lakes should remain in a meso-eutrophic state. In other lakes that received alum treatments but failed to express long term improvements (Jernelov 1970; Born 1979; Funk et al. 1980; and Knauer and Garrison 1980), either the major nutrient source was not diverted or the lake was polymictic. Mirror and Shadow lakes are monomictic infrequently, or at most, dimictic so wind mixing should not destroy the alum layer as was done in polymictic Pickerel Lake (Knauer and Garrison 1980). Cooke et al. (1978) suggested that internal loading from the littoral zone lead to increased in hypolimnetic phosphorus following an alum treatment. If this is happening in Mirror and Shadow Lakes, it must be happening at a slow rate. While sedimenting material will continue to fall on top of the alum layer in both lakes, the filling rate has decreased since the alum treatment as evidenced by the sedimentation traps. As the sediment increases, more phosphorus will undoubtedly be released into the overlying waters. Since the storm sewers have been diverted and most of the internal phosphorus loading has been eliminated, it is expected that with the decreased plankton productivity the sedimentation rate would be lower to near the level of pre-storm sewer days (0.064. cm/yr). Prior to 1930, the phosphorus levels in a sediment core were lower and Farris (1981) noted that the diatoms present were indicative of a less productive lake.

It will continue to be necessary to artificially circulate Mirror Lake at least in the fall to insure that winter fish kill will not occur. Because of its morphometry and location in a depression, Mirror Lake cannot be expected to completely mix on its own in the fall, therefore, the danger will continue that a fish kill may result.

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